

STAGES TO SATURN

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STAGES TO SATURN

STAGES TO SATURN

*A Technological History
of the
Apollo/Saturn Launch Vehicles*

Roger E. Bilstein

The NASA History Series



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*To
Wernher von Braun
1912–1977
and the men and women
who built the Saturn*

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Contents

	<i>Page</i>
FOREWORD	xi
PREFACE	xv
ACKNOWLEDGMENTS	xix
I. PROLOGUE	1
1. Concepts and Origins	3
II. THE SATURN BUILDING BLOCKS	23
2. Aerospace Alphabet: ABMA, ARPA, MSFC	25
3. Missions, Modes, and Manufacturing	57
III. FIRE, SMOKE, AND THUNDER: THE ENGINES	87
4. Conventional Cryogenics: The H-1 and the F-1	89
5. Unconventional Cryogenics: RL-10 and J-2	129
IV. BUILDING THE SATURN V	155
6. From the S-IV to the S-IVB	157
7. The Lower Stages: S-IC and S-II	191
8. From Checkout to Launch: The Quintessential Computer ..	235
V. COORDINATION: MEN AND MACHINES	259
9. Managing Saturn	261
10. The Logistics Tangle	293
VI. STEP BY STEP	321
11. Qualifying the Cluster Concept	323
12. The Giant Leap	347

STAGES TO SATURN

	<i>Page</i>
VII. EPILOGUE	379
13. Legacies	381
APPENDIX A—SCHEMATIC OF SATURN V	405
APPENDIX B—SATURN V PRELAUNCH—LAUNCH SEQUENCE	407
APPENDIX C—SATURN FLIGHT HISTORY	413
APPENDIX D—SATURN R&D FUNDING HISTORY	421
APPENDIX E—SATURN V CONTRACTORS	423
APPENDIX F—LOCATION OF REMAINING SATURN HARDWARE	439
APPENDIX G—NASA ORGANIZATION DURING APOLLO-SATURN	441
APPENDIX H—MSFC PERSONNEL DURING APOLLO-SATURN	449
NOTES	457
SOURCES AND RESEARCH MATERIAL	493
INDEX	501

Illustrations

	<i>Page</i>
Frontispiece—the Saturn V at LC-39	ii
Seven photos of <i>Apollo 11</i> mission	6
Photo of Robert Goddard	10
Photo of German rocket pioneers	10
Four photos of early rockets in the U.S.	16
Wernher von Braun with the first seven astronauts	20
Launch of Alan Shepard on Mercury-Redstone	20
Scale comparison of U.S. manned space flight vehicles	20
Development of Saturn concepts	28
Saturn I with Mercury-Redstone and Juno II	30
President Eisenhower with first NASA Administrator T. Keith Glennan and Deputy Administrator Hugh Dryden	32
Wernher von Braun with his ABMA senior staff	38
President Eisenhower dedicates the George C. Marshall Space Flight Center	43
Abe Silverstein tours rocket facility	46
Two summary charts from the Silverstein Report	49
Early versions of the Saturn C-1 and C-5	60
The stable of NASA launch vehicles	61
John Houbolt and Lunar Orbit Rendezvous	64
President Kennedy at MSFC	68
Four aerial views of MSFC	71
Photos of Michoud Operations and Mississippi Test Facility	75
Saturn I design and manufacture	82
Saturn IB design and manufacture	84

LIST OF ILLUSTRATIONS

	<i>Page</i>
Saturn engine applications	90
Turbopump for the H-1 engine	94
Specifics and systems of the H-1 engine	100
Firing and manufacture of the H-1 engine	105
Specifics and schematic of the F-1 engine	110
Engine start sequence for the S-IC stage	111
F-1 engine injector plate and turbopump	117
F-1 thrust chamber and brazing furnace	122
F-1 test stand	125
F-1 engine production line	126
Centaur stage with two RL-10 engines	136
RL-10 engine specifics and systems; engine cluster mounted in the S-IV stage of Saturn I	139
J-2 engine specifics, systems, assembly, and testing	151
Saturn S-IV stages	161
Seven photos of manufacturing the S-IVB stage	169
Comparison of S-IVB stages of Saturn IB and V	179
S-IVB stage rollout and testing	187
S-IC stage Saturn V launch vehicle	197
Five photos of skin fabrication for the S-IC stage	204
Six photos of assembly and testing of the S-IC stage	208
Seven photos of fabrication and assembly of the S-II stage	220
The mission control center at KSC	236
ST-124 inertial guidance platform	244
Instrument unit specifics, systems, and assembly	246
Wernher von Braun is briefed by Mathias Siebel	262
Saturn program major sites	268
Saturn contractors	268
Two organization charts of Saturn V program	272
Photo of Arthur Rudolph	273
NASA Office of Manned Space Flight Management Council	277
Manned Space Flight Awareness Program	279
Photo of MSFC's Saturn V program control center	286
S-IC flight stage at MSFC on its transporter	300
S-II stage on its transporter	303
Five photos of the NASA barge fleet	306
Four photos of Saturn air transport	316
<i>USNS Point Barrow</i>	319
Saturn transportation equipment	319
Three views of Saturn I test flights	326
Two views of Pegasus payloads for Saturn I	333
Cutaway drawing and two views of the Saturn IB launch vehicle	342
AS-501, first flight-ready Saturn V	343
Launch Complex 39	356
Mobile Service Structures at LC 39	365
<i>Apollo 8</i>	367
<i>Apollo 11</i> in flight; control room after launch; Astronaut Edwin Aldrin prepares to step onto lunar surface; lunar sample chest	373
<i>Apollo 17</i> lunar roving vehicle	377
Commonality of Saturn hardware	380
Two photos of Saturn and Skylab	385
Two views of Saturn and the Apollo-Soyuz Test Mission	389
Four photos of Huntsville, Alabama	395

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Foreword

Few of man's technological endeavors compare in scope of significance to the development of the Saturn family of launch vehicles.

At the time of this writing in 1979, we may still be too close to the project to see it objectively from the perspective of history, but I expect that future historians will compare the development of Saturn to such great and imaginative projects as the building of the Panama Canal and to such latter day technological achievements as the Manhattan Project. In terms of both vision and achievement, Saturn may surpass them all.

It was as if the Wright Brothers had gone from building their original Wright Flyer in 1903 to developing a supersonic Concorde in 1913. Unimaginable; yet in 10 short years the builders of Saturn progressed from the small, single-engine rockets like Redstone to the giant vehicle with clustered engines that put man on the moon. Our Earth-to-orbit weight-lifting capability grew in that decade by 10 thousand times.

Saturn was an engineering masterpiece. The ultimate Saturn, taller than the Statue of Liberty, had a takeoff weight that exceeded that of 25 fully loaded jet airliners, and produced as much power as 85 Hoover Dams.

The Saturn program was also a masterpiece of management. There are those who hold that one of the principal benefits this country derived from the Apollo-Saturn lunar landing program was the development of a new and extraordinary management approach through which the National Aeronautics and Space Administration directed vast human and material resources toward a common purpose. The system that was developed to meet the incredible complexities of the program, taking account of its pioneering nature and the time constraint imposed, provides a pattern for managing a broad spectrum of future technological, scientific, and social endeavors.

One of the most remarkable things about the Saturn program was its success rate. An early press release openly stated that because of the

STAGES TO SATURN

complexity of the system and the tremendous advancement in technology required, program officials fully expected half of the 10 Saturn I's launched to fail. None did. Neither did any Saturn IB, nor did any Saturn V, either test vehicle or operational rocket—and there were 32 Saturn launches in all.

The reliability assessment of the system was such that only two Saturn Vs were launched before the third sent Frank Borman's crew around the moon during Christmas of 1968. In all, 27 men went around the moon aboard Saturn-launched space vehicles, 12 actually walked on its surface.

Close on the heels of the lunar landing series, NASA developed Skylab, the world's first major laboratory in which we could operate experiments in the new environment of space. The Saturn again played a pivotal role in this enterprise—the core component of the Skylab itself being a modified Saturn stage. Only a Saturn V could lift the huge laboratory into orbit, which, when an Apollo spacecraft was annexed, weighed 100 metric tons and was 36 meters long. The three crews, which inhabited the space station for a total time of nearly six months, were launched on the smaller Saturn IBs. The Saturn family made Skylab possible, so Saturn deserves a large share of the credit for the mission's success in establishing a broad foundation of scientific and technological knowledge.

Furthermore, we should not overlook the role Saturn played in the Apollo-Soyuz Test Project of 1975. It was another Saturn IB that carried an American crew to its historic rendezvous with two Soviet cosmonauts in orbit. The reliable Saturn gave NASA every confidence that its crew could ascend on schedule following the Soviet launch half a world away and make the time-critical union of those two small objects in space. We had a high level of confidence that this, the last Saturn, would perform with the same excellence as its 31 predecessors. It did not disappoint us.

It should be pointed out that the Apollo-Saturn program was a national achievement. It has been estimated that 20 000 private firms and 300 000 people participated in the development of this system. The challenge taxed American ingenuity to the extreme. The result, of course, was that American technology made the "giant leap" referred to by Neil Armstrong. Whole new industries were born, offering products that touch our everyday lives in ways we could not have dreamed of just a decade before.

We may not soon again face a challenge to match the lunar landing, and it may be some time before we mount the kind of scientific and engineering effort that gave us Saturn. Whenever that next challenge comes, we have in the Apollo-Saturn program the basic blueprint for achieving success. It not only will point the way but will also give the confidence needed to undertake new and dramatic challenges.

FOREWORD

Among the other lessons learned from the development of Saturn is the evidence of how much a free society can do and how far a dedicated people can go when they are properly challenged, led, motivated, and supported.

This is our legacy from Saturn.

June 1979

William R. Lucas
*Director, George C. Marshall
Space Flight Center*

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Preface

The gigantic Saturn V launch vehicle may well be the first and last of its kind. Subsequent space ventures will be based on new vehicles, such as the smaller, reusable Space Shuttle. Manned launches in the near future will be geared to orbital missions rather than planetary excursions, and unmanned deep-space missions will not demand the very high thrust boosters characteristic of the Apollo program. As the space program moves into the future, it also appears that the funding for elaborate "big booster" missions will not be forthcoming for NASA. The Saturn V class of launch vehicles are the end of the line of the Saturn generation. It is not likely that anything like them will ever be built again.

Because of the commanding drama of the awesome Saturn V, it is easy to forget the first Satellites—the Saturn I and Saturn IB. This history is an attempt to give due credit to these pioneering vehicles, to analyze the somewhat awkward origins of the Saturn I as a test bed for static testing only, not as an operational vehicle, and to discuss the uprated Saturn IB as an interim booster for the orbital testing of the first Apollo capsules. Evolution of the engines is also given considerable space early in the narrative. Because the Apollo-Saturn program was expected to put a man on the moon within a fixed time span, the use of available hardware was particularly attractive—an aspect of the program that is not generally appreciated by the public. The development of the early Saturn I and IB vehicles, as well as the engines, illustrates this approach. Inevitably, the unique nature of the mission called for advances in the state of the art, and the Saturn history includes some examples. One outstanding example is the development of high-energy liquid hydrogen engines. Other examples include the development of insulation for extended storage of large quantities of hydrogen in vehicle tanks and the advances in the computer technology of the guidance and control systems.

The development of Saturn was enormously expensive and time-consuming. Even given the expected costs of developments to advance the state of the art, why were the costs of the development time so great if

STAGES TO SATURN

the program still relied so much on existing hardware? Part of the answer involves the uniqueness of dimensions. Even a proven component, to be used in the huge Saturn, had to be scaled up in size. The larger component had to withstand a similar increase in the amount of punishment inflicted on it, and this fact opened up a whole new regime of operational headaches. The scaling up of components and systems for lunar missions seemed to involve geometrical progressions rather than simple arithmetic progressions. The F-1 engines for the S-IC first stage graphically illustrate this difficulty. The size of the Saturn stages and engines also called for enlargement of test stands and other facilities, with attendant increases in time and costs. The logistical challenge assumed gargantuan proportions. The managers of the Apollo-Saturn programs also discovered unanticipated expenses in storing and maintaining exotic hardware that was subject to degradation unless constantly monitored, refurbished, and attended by additional cadres of technicians.

This book is a technological history. To many contemporaries the narrative may read too much like a technical manual, but the author's concern is for posterity, when the technical manuals may be lost or dispersed (as many are already) and knowledgeable participants have long since died. The narrative approach was largely predicated on questions that might well be asked by future generations: How were the Satellites made? How did they work? Two other histories, already published, deal with subjects keyed to the Apollo-Saturn program: (1) the development of the Apollo command and service modules along with the lunar module, and (2) the construction and operation of launch facilities at Cape Kennedy. These books contain much of the political and administrative struggles surrounding the origins and development of the Apollo program, and it would be redundant to retell the whole story for the Saturn history. I have therefore included only the background that seemed necessary to put the Saturn in proper perspective, and Part Two recapitulates the programmatic and administrative origins of Saturn. The bulk of the text is devoted to the theme of technological development. Even chapter 9, on management, is geared to the specifics of the technological management of Saturn vehicles.

The decision to treat the history of the Saturn program as a technological narrative shaped the nature of all sections of the book. So that some of the innovations and advances might be appreciated, it seemed advisable to include a brief historical overview of rocket technology. Against this background, I hope the Saturn story will stand out with greater clarity.

The narrative itself is organized into seven parts. The question was how to deal with the complexity of many simultaneous programs during the Saturn development that involved the various engines, stages, and associated equipment for three separate launch vehicles. A strict chronological organization seemed unnecessarily confusing. The topical approach,

PREFACE

although constructed in a loose chronological sequence, provided the opportunity to deal with the early technology involved in Saturn I and Saturn IB launch vehicles primarily in terms of the concept of clustering tanks and engines. The engines themselves, although they possessed inherent differences, evolved out of common principles of engine design and cryogenic technology. Dealing with these propulsion systems as a separate unit made the significance of their development stand out more clearly. Similarly, I analyzed the evolution of rocket stages as a unit and emphasized propellant tankage for the Saturn V vehicle. Although many early Saturn flights were concurrent with the research and development phases, all the launches are summarized in two chapters toward the end of the book. Just as the flights were the culmination of Apollo-Saturn, discussion of them all at the end of the narrative seemed logical.

The manned operations involving the spacecraft—the activities of the launch crews at liftoff—the role of the astronauts—these events involved discrete numbers of human actors. The inherent drama in launches and missions tended to spotlight the people involved. On the other hand, development of the Saturn launch vehicle rested on millions of hours of prior research and development and on thousands of designers, engineers, technicians, and specialists who worked behind the scenes. It was often impossible to single out a specific individual responsible for a specific achievement because most of the major decisions and breakthroughs resulted from elaborate team efforts. In fact, one veteran of the Marshall Space Flight Center told me that he preferred that the Saturn history not mention people at all. It was too hard, he explained, to isolate significant achievements without mentioning dozens of people who made successful contributions.

The launch vehicle, as dramatic as it was during liftoff, played a minor role in the total duration of a mission. It was visible to observers for only eight minutes or so as it blazed into orbit. The personnel of Houston's Mission Control and the astronaut crew occupied center stage for the lion's share of the lunar mission. For all the spectacular effects of the Saturn vehicle's awesome launch, most of the Saturn story deals with many years of unglamorous research, development, and test. It is a story of prior work: of nuts, bolts, and pyrotechnics—and that is the story I have tried to tell in these pages.

June 1979

R.E.B.
Houston

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Acknowledgments

Dr. Rudolph Hermann, Director of the Research Institute of the University of Alabama at Huntsville (UAH), encouraged much of the early work of the Saturn history project. His successor, Dr. John F. Porter, Jr., and Dr. J. Edwin Rush, Director of Graduate Programs and Research at UAH, provided continuing encouragement and support.

Frederick I. Ordway III and David L. Christensen were primarily responsible for acquiring specialized documentation under the UAH contract. With unusual accuracy and efficiency, Mrs. M. L. Childress helped set up the documentary files and their annotated index and typed several early drafts of the history. John Stuart Beltz, one of the original historians on the project, drafted several "working papers" on aspects of the Saturn program that were helpful in preparing the final manuscript. Beltz conducted several interviews and acquired contractor documentation, particularly concerning the S-II stage of the Saturn V. Many long conversations with him helped shape this and other parts of the Saturn narrative. Mitchell R. Sharpe of George C. Marshall Space Flight Center developed working papers and bibliographies on early rocket history and assisted in acquiring materials on Saturn management (chapter 9) and the "all-up" launch of the first Saturn V (chapter 12).

At the MSFC Historical Office, David S. Akens, Leo L. Jones, and A. Ruth Jarrell offered continuous assistance. After the office was abolished, Robert G. Sheppard, Don Lakey, and Betty Davis helped fill requests for additional information and coordinated the distribution of preliminary copies of the manuscript within MSFC for editorial comment. Bonnie Holmes, in the MSFC Director's Office, provided invaluable help during a follow-up research visit to MSFC during the summer of 1975 and helped acquire photographs and drawings.

During the final phases of completing the manuscript, the documents of the Saturn history project were temporarily transferred to the Johnson Space Center (JSC) near the University of Houston/Clear Lake City (UH/CLC) campus. James M. Grimwood, JSC Historian, not only

STAGES TO SATURN

provided shelf space for these documents but also provided office facilities, access to the coffee pot, encouragement, and advice. My debt to him is considerable. I wish to thank Sally Gates and my other colleagues, also of JSC, at work on NASA histories: Edward and Linda Ezell and David Compton, whose interest and suggestions were unfailingly helpful. At UH/CLC, Dr. Calvin Cannon, Dean of Human Sciences and Humanities, and Dr. Peter Fischer, Director of Programs in Humanities, generously cooperated in arranging teaching duties to benefit research and writing. Special thanks go to Jean Sherwood and Myra Hewitt Young who worked so cheerfully and conscientiously in typing the manuscript.

Dr. Eugene M. Emme, of the History Office at NASA Headquarters in Washington, D.C., organized and guided the NASA historical program and monitored the Apollo-Saturn history effort. Lee Saegesser, archivist in the History Office, invariably turned up needed illustrations and documents. I owe a special debt, however, to Dr. Monte D. Wright, Director of the History Office, and Dr. Frank W. Anderson, Jr., Publications Manager, for their painstaking and thorough editing of early drafts of the manuscript. I learned much from their criticisms, and the manuscript, I trust, is much the better for their close attention to it. I would like to emphasize here that I have had complete freedom in interpreting the Saturn program in my own way. I was only cautioned at one point *not* to write in such a way to open myself to the charge of delivering a "company history."

Personnel from NASA and contractors' offices all over the United States diligently and graciously responded to requests for additional illustrations and documentation. Dozens of NASA and contractor personnel (the majority of whom still remain unknown to me) read various drafts of the manuscript and returned copies with suggestions and corrections. Since I cannot possibly identify and list all of them, I can only acknowledge my great obligation to their interest in this history of Saturn. Likewise, I want to acknowledge the cooperation extended by the dozens of NASA and contractor personnel who consented to interviews. As for any remaining errors of fact or interpretation, they are mine.

Portions of this text have appeared elsewhere, and I wish to acknowledge the following publications and editors for cooperation in incorporating revised versions in the present text: "Aircraft for the Space Age: The Guppy Series of Transports," *Aerospace Historian* (Summer 1974); "From the S-IV to the S-IVB: The Evolution of Rocket Stage for Space Exploration," *Journal of the British Interplanetary Society* (December 1979); "To Make a Giant Leap: Rocket Engines for Manned Lunar Missions," in Kent Newmyer, ed., *Historical Essays in Honor of Kenneth R. Rossman* (Doane College, Crete, Neb., 1980).

I could never have finished the history of Saturn without the affection and encouragement of my wife Linda and without the heart-warming interest of Paula and Alex in "the rocket book."

I

Prologue

The passage of time blurs many details. Part One is intended to bring back into focus some of the facts, circumstances, and background of space exploration. The opening section of chapter 1 briefly recapitulates the flight of *Apollo 11*—the first lunar landing mission—and provides the opportunity to introduce some of the hardware and nomenclature of the Apollo-Saturn program. A historical overview of rocketry, including the main threads of Saturn's origins, provides a background for the scope and boldness of *Apollo 11* and the Saturn adventure in the chapters that follow.

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I

Concepts and Origins

Movement of the rocket from the assembly site to the launch pad was scheduled for 20 May 1969. In slow sequence, the 142-meter-high doors ponderously opened, retracting upward like a vertical accordion, revealing the launch vehicle inside the huge gray structure known as the Vehicle Assembly Building. As the folding doors moved higher, the bright morning sun highlighted the whiteness of the three-stage launch vehicle with its scarlet lettering and black markings. Most of the American public, and the world, knew the towering 111-meter rocket as the Saturn V or the Apollo 11. To the men and women who built it, it was known better by its official designation: AS-506. Whatever its name, everyone knew its destiny. This rocket was going to be the first to land men on the moon.

Other Saturn rockets had preceded it. From Kennedy Space Center (KSC), the National Aeronautics and Space Administration's facility on Florida's Atlantic coast, 10 Saturn I vehicles were launched from 1961 to 1965, and five Saturn IB vehicles were launched between 1966 and 1968.¹ Prior to the launch of *Apollo 11*, between 1967 and 1969 NASA launched two unmanned Saturn V rockets and three manned vehicles in qualifying flights. The manned lunar landing was the payoff. This mission, with astronauts Neil Armstrong, Edwin Aldrin, and Michael Collins as the crew, commanded attention as none before had done.

THE FLIGHT OF AS-506

The launch of AS-506 took place on schedule. Ignition occurred at 31 minutes and 50 seconds past 9:00 a.m., and seconds later, the rocket left Earth, bound for the moon, at 9:32 a.m. EDT, 16 July 1969.

STAGES TO SATURN

The intricacies of a successful lunar mission dictated a multiphased operation, and the Saturn V was a multistage rocket. Early plans for the moon rocket included proposals for a comparatively simple "one-shot" vehicle in the form of a single-stage rocket. For all the attraction of the basic simplicity of a single-stage rocket as compared with a multistage vehicle, designers finally discarded it. The single-stage concept would have required a rocket of great girth and structural strength to carry all the required propellants. As a single-stage vehicle climbed into space, a considerable weight penalty developed because all the weight of the empty tankage had to be carried along. This weight penalty severely limited the size of the payload—in this case, a manned spacecraft. The multistage design allowed the first stage, with its big booster engines, to drop off once its rocket propellants were depleted. The second stage was more efficient because it had relatively less weight to push further into the planned trajectory, and it benefited from the accelerative forces imparted to it by the first stage. By the same token, the third stage had an even lighter weight and an even higher acceleration. In addition, the multistage approach permitted the use of special high-energy fuels in the upper stages. These considerations played a large role in the development of the Saturn V as a three-stage launch vehicle.

For the Apollo 11 mission, components of the Saturn V launch vehicle and the Apollo spacecraft had arrived in segments at Cape Kennedy. Whether they reached their destination by ship, barge, plane, or truck, they were all consigned for delivery to the Vehicle Assembly Building (VAB). Inside, they were stacked together to make up the moon rocket. The VAB was the heart of NASA's mobile launch concept, a radical departure from earlier tradition in rocket launching. Previous custom was to "stack" (assemble) the rocket at the launch pad itself, with minimal protection from the elements afforded by a comparatively makeshift structure thrown up around the rocket and its launching tower.

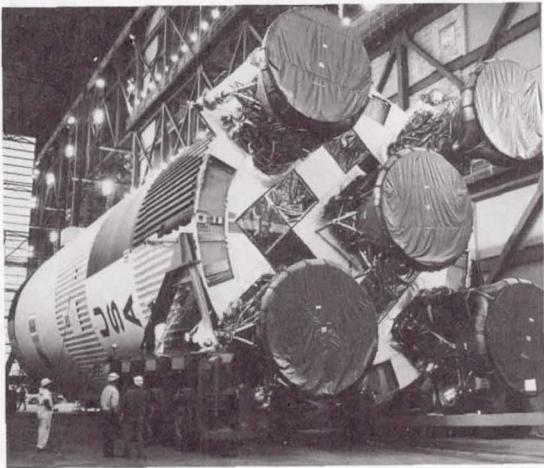
This approach completely tied up the launch pad during the careful stacking procedures and lengthy checkout. The size and complexity of the Saturn V dictated a change in tactics. NASA was planning a heavy schedule of Saturn launches and simply could not accept the consequent tie-up of launch sites. In a bold new approach, NASA implemented the mobile launch concept, which entailed the erection and checkout of several of the three-stage vehicles and spacecraft inside one gargantuan building, the VAB, with equipment to move the readied vehicles to a nearby launch site. At KSC's Launch Complex 39, a small army of engineers and technicians received components of the Saturn V, checked them out, assembled the complete vehicle, and conducted the launch. The facilities of the sprawling complex included the VAB, the mobile launcher, the crawler-transporter, the crawlerway to the launch pad, the mobile service structure, and the launch pad itself.²

CONCEPTS AND ORIGINS

The first stage of Saturn V, the S-IC, employed a cluster of five F-1 engines of 6 672 000 newtons (1 500 000 pounds) of thrust each, for a total of 33 360 000 newtons (7 500 000 pounds) of thrust. The first-stage propellant tanks contained 767 cubic meters (203 000 gallons) of RP-1 fuel (a kerosene-type fuel) and 1251 cubic meters (331 000 gallons) of oxidizer (liquid oxygen, or LOX). The S-IC consumed these propellants in a fiery holocaust lasting only 2.5 minutes, by which time the Saturn V was boosted to a speed of about 9700 kilometers per hour at the cutoff altitude of around 61 kilometers. The spent first stage fell away, to fall into the sea, and the S-II second stage took over. Like the first stage, the S-II also mounted a cluster of five engines, but these were the 1 112 000 newtons (250 000 pounds) of thrust J-2 type, burning liquid hydrogen as fuel, and using liquid oxygen as the oxidizer. In the course of its six-minute "burn," the second stage propelled the Saturn V to an altitude of 184 kilometers, accelerating to a speed of 24 620 kilometers per hour. At this point, the Saturn vehicle had nearly reached the speed and altitude for Earth orbit. After the second stage dropped away, following its precursor into the ocean, the S-IVB third stage then hurtled the 113 400-kilogram payload into a 190-kilometer orbit, using its single J-2 engine for a burn of 2.75 minutes. In this final part of the orbital mission sequence, the remainder of the launch vehicle and its payload barreled into orbit at a speed of 28 200 kilometers per hour.

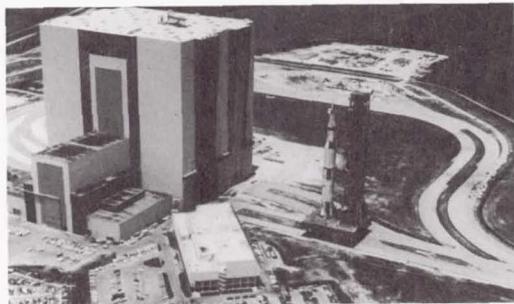
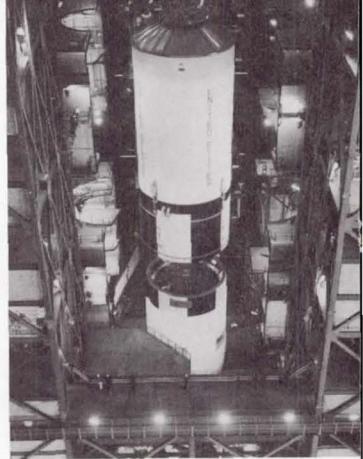
The S-IVB did not deplete its fuel during the third-stage burn, because the mission called for the S-IVB to reignite, firing the spacecraft out of Earth orbit and into the translunar trajectory to the moon. During the parking orbit (one to three circuits of the Earth), Astronauts Armstrong, Aldrin, and Collins completed a final check of the third stage and the spacecraft, while ground technicians analyzed telemetry and other data before making the decision to restart the J-2 for the translunar trajectory burn. No problems showed up to suggest the possibility of terminating the flight, so mission personnel waited for the precise moment in Earth orbit for the last five-minute operation of the Saturn V launch vehicle. Two hours and 44 minutes after liftoff, over the southern Pacific, the S-IVB ignited and accelerated the spacecraft to 39 400 kilometers per hour—enough to carry the spacecraft out of Earth orbit and place it in a trajectory bound for the moon. The third stage was not immediately separated from the rest of the spacecraft. First, the command and service module (CSM) separated from the lunar module adapter, reversed itself and performed a docking maneuver to pull the lunar module away from the now spent third stage and the instrument unit. This transposition and docking maneuver signaled the end of the Saturn V launch vehicle's useful life.

As Armstrong, Aldrin, and Collins accelerated toward the moon with the lunar module anchored to the CSM, the S-IVB and the instrument unit were left behind in space. With both the spacecraft and

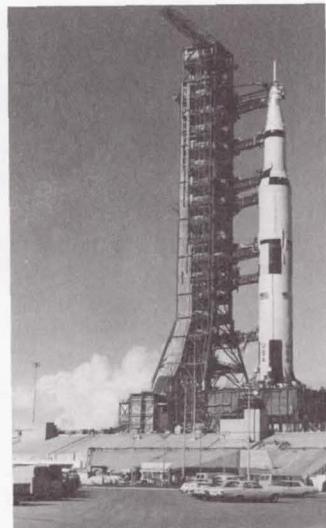


Apollo 11 16-24 July 1969

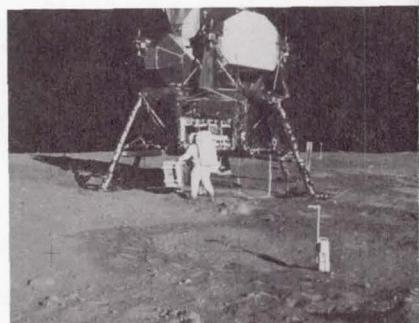
Left, the big S-IC stage of Apollo 11 arrived at Kennedy Space Center in February 1969. In March the S-II second stage (right) is mated to the first stage.



In May Apollo 11 rolls out of the Vehicle Assembly Building on its crawler (above) and arrives at Launch Complex 39 (right).



On 16 July, Apollo 11 is launched (left); 2.5 minutes later the first stage separates and the second-stage engines ignite (right). On 20 July the first men walked on the moon (right, below).



CONCEPTS AND ORIGINS

the third stage still in lunar-oriented trajectories, mission planners wanted to minimize the chances of the two elements colliding with each other. The spacecraft performed a three-second burn with its service propulsion system to impart a velocity increase of six meters per second. This procedure not only widened the distance between the two, but also put the spacecraft and the three-man crew into a free-return trajectory, which used the lunar gravitational field to aid in a return to Earth in case the lunar landing had to be aborted. NASA also wanted to avoid the chances of the S-IVB impacting into the lunar surface in the vicinity of the astronauts' landing zone, so an automated sequence triggered a dump of residual propellants in the S-IV to realign the third stage's trajectory in such a way that the moon's gravitational field increased the S-IVB's velocity in a different direction. This "slingshot" maneuver was effective enough to throw the stage into solar orbit, where it would eventually impact into the sun in a dramatic demise.³

PYROTECHNIC PIONEERING

In its soaring flight out of the dominance of Earth's gravity, *Apollo 11* marked one of the great milestones in rocket technology. The chemical and solid propulsion systems of the Saturn V and the Apollo spacecraft represented the distillation of concepts and plans and work by a host of people who had continuously worked toward the goal of manned lunar exploration. The rocket itself—the Saturn V—represented the culmination of generations of technological and theoretical work stretching all the way back to the 13th century.

There was one common denominator for the military, whaling, and life-saving rockets from antiquity through World War I: they were powder-burning, or "solid," rockets. A solid rocket, although simple, had several shortcomings. The rate of thrust after ignition of the rocket could not be controlled; there was no guidance after the launch; the powder technology at the turn of the century seemed to dictate a missile with an optimum weight of about 68 kilograms (most were in the 14–23-kilogram category); and the range rarely exceeded 2700 meters. Advances in artillery in the late 19th century had already displaced the rocket as an effective weapon.⁴ For space exploration, solid-fueled rockets seemed to lack the thrust potential for extreme range or for reaching high altitudes. Visionaries who were thinking of using rockets for space exploration had to consider other sources for fuel, and there were still the problems of guidance, as well as the problem of human survival in the space environment.

At the same time that powder rockets began to fall from favor in the late 19th century, a realistic theory and development of space flight, with a strong interest in new types of propellants, was beginning to evolve.

STAGES TO SATURN

Three pivotal figures in the new era of rocket technology were Konstantin Tsiolkovsky (1857–1935), Robert H. Goddard (1882–1945), and Hermann Oberth (1894–). They were imaginative men who drew their theories and experiments from the growing bank of science and technology that had developed around the turn of the century. For one thing, the successful liquefaction of gases meant that sufficient quantities of fuel and oxidizer could be carried aboard a rocket for space missions. Research into heat physics helped lay the foundations for better engine designs, and advances in metallurgy stimulated new standards for tanks, plumbing, and machining to withstand high pressures, heat, and the super-cold temperatures of liquefied gases. Progress in mathematics, navigational theory, and control mechanisms made successful guidance systems possible.

Although Tsiolkovsky did not construct any working rockets, his numerous essays and books helped point the way to practical and successful space travel. Tsiolkovsky spent most of his life as an obscure mathematics teacher in the Russian provinces, but he made some pioneering studies in liquid chemical rocket concepts and recommended liquid oxygen and liquid hydrogen as the optimum propellants. In the 1920s, Tsiolkovsky analyzed and mathematically formulated the technique for staged vehicles to reach escape velocities from Earth. In contrast to the theoretical work of Tsiolkovsky, Robert Goddard made basic contributions to rocketry in flight hardware. Following graduation from Worcester Polytechnic Institute, Goddard completed graduate work at Clark University in 1911 and became a member of the faculty there. In the 1920s, he continued earlier experiments with liquid-fueled vehicles and is credited with the first flight of a liquid-propellant rocket on 16 March 1926. With private support, Goddard was able to pursue development of larger rockets; he and a small crew of technicians established a test site in a remote area of the Southwest not far from Roswell, New Mexico. From 1930 to 1941, Goddard made substantial progress in the development of progressively larger rockets, which attained altitudes of 2300 meters, and refined his equipment for guidance and control, his techniques of welding, and his insulation, pumps, and other associated equipment. In many respects, Goddard laid the essential foundations of practical rocket technology, including his research paper entitled “A Method of Attaining Extreme Altitude” (published by the Smithsonian Institution in 1919)—a primer in theory, calculations, and methods—and his numerous patents that comprised a broad catalog of functional rocket hardware. In spite of the basic contributions of Tsiolkovsky in theory, and of Goddard in workable hardware, the work of both men went largely unheralded for years. Tsiolkovsky’s work remained submerged by the political conditions in Russia and the low priority given to rocket research prior to World War II. Goddard preferred to work quietly, absorbed in the immediate problems of

CONCEPTS AND ORIGINS

hardware development and wary of the extreme sensationalism the public seemed to attach to suggestions of rocketry and space travel.

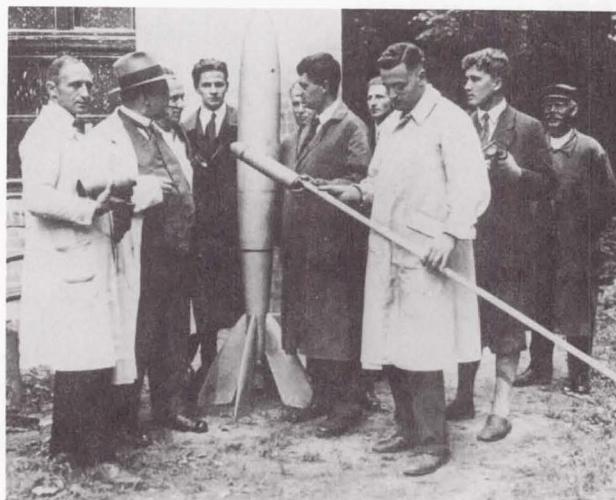
Although the work of Hermann Oberth was original in many respects, he was also significant as advocate and catalyst because he published widely and was active in popularizing the concepts of space travel and rocketry. Born in Transylvania of German parentage, Oberth later became a German citizen. He became interested in space through the fictional works of H.G. Wells and Jules Verne and left medical school to take up a teaching post where he could pursue his study and experimenting in rocketry. Oberth's work was independent of Tsiolkovsky's, and he heard of Goddard's brief paper of 1919 just as his own book, *The Rocket into Planetary Space*, was going to press in 1923. *The Rocket into Planetary Space* was read widely, translated into English, and was the precursor of many other books, articles, and lectures by the energetic author. Oberth analyzed the problems of rocket technology as well as the physiological problems of space travel, and his writings encouraged many other enthusiasts and researchers. In 1928, Oberth and others were consultants for a German film about space travel called *The Girl in the Moon*. The script included the now-famous reverse countdown before ignition and liftoff. As part of the publicity for the movie, Oberth and his staff planned to build a small rocket and launch it. The rocket was only static-fired and never launched, but the experience was a stimulating one for the work crew, including an 18-year-old student named Wernher von Braun.

During the ensuing years, Oberth continued to teach while writing and lecturing on space flight, and he served as president of the Verein fur Raumschiffahrt (VfR) (Society for Space Travel), which had been formed in 1927. The existence of organized groups like the VfR signaled the increasing fascination with modern rocketry in the 1930s, and there were frequent exchanges of information among the VfR and other groups like the British Interplanetary Society and the American Interplanetary Society. Even Goddard occasionally had correspondence in the American Interplanetary Society's *Bulletin*, but he remained aloof from other American researchers in general, cautious about his results, and concerned about patent infringements. Because of Goddard's reticence, in contrast to the more visible personalities in the VfR, and because of the publicity given the German V-2 of World War II, the work of British, American, and other groups has been overshadowed. If not as spectacular as the work on the V-2 rockets, their work nevertheless contributed to the growth of rocket technology in the prewar era and the successful use of a variety of Allied rocket weapons in the war. Although groups such as the American Interplanetary Society (which later became the American Rocket Society) succeeded in building and launching several small rockets, much of their significance lay in their role as the source of a growing number of technical papers on rocket technologies. But rocket

STAGES TO SATURN

development was complex and expensive. The costs and the difficulties of planning and organization meant that sooner or later the major work in rocket development would occur under the aegis of permanent government agencies and government-funded research bodies.⁵

In America, significant team research began in 1936 at the Guggenheim Aeronautical Laboratory of the California Institute of Technology. In 1939 this group received the first Federal funding for rocket research. Research on rockets to assist aircraft takeoff was especially successful. The project was known as JATO, for Jet-Assisted Take-Off, because the word rocket still carried negative overtones in many bureaucratic circles. During World War II, U.S. armed forces made wide use of the bazooka (an antitank rocket) as well as a variety of barrage rockets launched from ground batteries or from ships, and high-velocity air-to-surface missiles. The JATO work also led to the development of a significant liquid-fueled rocket, a two-stage Army ballistic missile with a solid booster known as the



U.S. rocket pioneer Robert H. Goddard poses beside his rocket (left) before it achieved the first flight by a liquid-fueled rocket on 16 March 1926. In Germany (above) a rocket demonstration was held in August 1930 at the Chemish-Technische Reichsansalt (equivalent to the U.S. Bureau of Standards). Standing to the right of the rocket is Hermann Oberth; youthful Wernher von Braun is second from the right.

CONCEPTS AND ORIGINS

Wac Corporal. The first-stage booster, adapted from an air-to-ground rocket dubbed the Tiny Tim, developed 222 000 newtons (50 000 pounds) of thrust, and the second stage, filled with nitric acid-aniline liquid propellants, developed 6700 newtons (1500 pounds) of thrust, a combination that fired a payload up to an altitude of 69 kilometers. But the Corporal program did not reach full development until after 1945.⁶ The most striking military rocket of the wartime era came from Germany.

THE LEGACY OF PEENEMUENDE

In the early 1930s, the VfR attracted the attention of the German Army because the Treaty of Versailles, which restricted some types of armaments, left the door open to rocket development, and the military began rocket research as a variation of long-range artillery. Captain Walter Dornberger, an Army artillery officer with advanced degrees in engineering, spearheaded military rocket development. One of his chief assistants was a 20-year-old enthusiast from the VfR, Wernher von Braun, who joined the organization in October 1932. By December 1932, the Army rocket group had static-fired a liquid-propellant rocket engine at the Army's proving ground near Kummersdorf, south of Berlin.

Wernher von Braun was born in 1912 at Wirsitz, Germany, in Posen Province, the second of three sons of Baron and Baroness Magnus von Braun. A present of a telescope in honor of his church confirmation started the youthful von Braun's interest in space, spurring him to write an article about an imaginary trip to the moon. Fascination with the prospects of space travel never left him, and in 1930 he joined the VfR, where he met Oberth and other rocket enthusiasts. At the same time, he attended the Charlottenburg Institute of Technology and did apprentice work at a machine factory in Berlin. Before completing his bachelor's degree in mechanical engineering in 1932, he had participated in the space-travel film project and had come into contact with German ordnance officers. This contact led to the Army's support of von Braun's doctoral research in rocket combustion, which he completed in a brief period of two years, and he received his degree from Friedrich-Wilhelms-Universität of Berlin in 1934.⁷

By the next year, it became evident that the available test and research facilities at Kummersdorf were not going to be adequate for the scale of the hardware under development. A new location, shared jointly by the German Army and Air Force, was developed instead. Located on the island of Usedom in the Baltic, the new Peenemuende facility (named for the nearby Peene river) was geographically remote enough to satisfy military security and boasted enough land area, about 52 square kilometers, to permit adequate separation of test stands, research facilities, production areas, and residential sections. Test shots could be fired into

STAGES TO SATURN

the Baltic Sea, avoiding impact in inhabited regions. Starting with about 80 researchers in 1936, the facility comprised nearly 5000 personnel by the time of the first launch of the V-2 in 1942. Later in the war, with production in full swing, the work force numbered about 18 000.

The V-2 (from *Vergeltungswaffen-2*, or “weapon of retaliation”) had no counterpart in the Allied inventory. The V-2 was 14 meters long, with a diameter of 1.5 meters, and capable of speeds up to 5800 kilometers per hour to an altitude of 100 kilometers. By the end of the war, Germany had launched nearly 3000 of the remarkable V-2 weapons against targets in England and elsewhere in western Europe at ranges up to 320 kilometers. With the support of government, private, and university sources for research and development, the von Braun team at Peenemuende solved numerous hardware fabrication problems and technical difficulties (such as the production, storage, and handling of liquid oxygen in large quantity), while developing unique management skills in rocket technology.⁸

Early in the V-2 development program, its creators began looking at the rocket in terms of its promise for space research as well as for military applications. The continuous undercurrent of fascination with space travel was real enough to land von Braun in the clutches of the Gestapo. Late in the war, the German SS made attempts to wrest control of Peenemuende from Dornberger. After von Braun himself turned down direct overtures from SS chieftain Heinrich Himmler, he was arrested at two o’clock one morning by a trio of Gestapo agents. Following two weeks of incarceration in prison at Stettin, von Braun was hauled into an SS court to hear the charges against him. Among other accusations, his prosecutors accused him of opposing the V-2 strikes on England and charged that he was more interested in rocketry for space research than in rocketry for warfare. Dornberger had to intercede directly with Adolf Hitler to get von Braun released.

By early 1945, it was apparent that the war was nearing its end. Von Braun called a secret meeting of his top staff and reviewed their options: stay on at Peenemuende in the face of the advancing Russian units or try to head south and surrender to the Americans. There was no dissent—go south. In railroad cars, trucks, and automobiles emblazoned with red and white placards reading *Vorhaben zur besonderen Verwendung* (Project for Special Disposition), the Peenemuende convoy bluffed its way through military and Gestapo checkpoints, arriving in the Harz mountain region in Bavaria with tons of documents and hundreds of Peenemuende personnel and their families. After regrouping, the von Braun team, unaware that the United States was already formulating a program to round up leading German scientific and technical personnel, began making plans for contacting the Americans. Best known as Operation Paperclip, the American search for the von Braun team had top priority.⁹

CONCEPTS AND ORIGINS

On 2 May 1944, von Braun's younger brother Magnus climbed on a bicycle and set off down a country road in search of the Americans. Magnus was delegated for this delicate mission because he spoke better English. Contact was established, and several months of effort cleared the bureaucratic hurdles and prepared the way for over 100 selected German personnel to come to the United States. Finally, von Braun and six others arrived at Fort Strong in Boston on 29 September 1945. If the vanguard found the circumstances of their entry into the United States somewhat confusing and disorganized, they found American rocket development in much the same state of affairs.¹⁰

EARLY POSTWAR AMERICAN ROCKETRY

The National Security Act of 1947 established a unified military organization under the Secretary of Defense, with separate and equal departments for the U.S. Navy, U.S. Army, and U.S. Air Force. In the nascent field of military rocketry, guidelines for responsibilities of research, development, and deployment were decidedly fuzzy. As a result, American missile development in the postwar era suffered from interservice rivalry and lack of strong overall coordination, a situation that persisted to the mid-1950s. The Air Force, successful in long-range bombardment operations during the war, made a strong case for leadership in missile development. On the other hand, the Navy worked up studies showing the capabilities of missile operations from ships and submarines, and the Army viewed missiles as logical adjuncts to heavy artillery. But the Air Force had initiated long-range missile development even before the end of the war, and this momentum gave them early preeminence in the field of missile development.

Because American missile technology did not yet have the capability for large rocket-propelled vehicles, the Air Force at first concentrated on winged missiles powered by air-breathing turbojet powerplants. The Air Force stable of cruise missiles possessed ranges from 1000 to 11 000 kilometers and were capable of carrying the heavy, awkward nuclear warheads produced in the early postwar era. Until the Atomic Energy Commission made lighter and less unwieldy warheads available, the Air Force pressed on with cruise missiles at the expense of development of rocket-powered intercontinental ballistic missiles (ICBMs) such as the Atlas. The Navaho project represented the peak of the cruise missile. Weighing in at 136 000 kilograms and capable of Mach 3 speeds, the Navaho's research and development costs came to \$690 million. It never reached operational status before cancellation in 1957, when ICBM technology overtook it. The Navaho made three successful flights, and the fallout from certain aspects of Navaho research and development

STAGES TO SATURN

turned out to be very significant in other areas. The experience in high-speed aerodynamics was applied to other aeronautical research programs, and the missile's all-inertial guidance system found application in ICBMs' and submarine navigational systems. Moreover, the booster units for Navaho were noteworthy in ICBM designs. Even though the Navaho used a ramjet engine for sustained flight to the target, the heavy vehicle was boosted into the air by three liquid-propellant rocket engines of 600 000 newtons (135 000 pounds) of thrust each. Developed by Rocketdyne (a division of North American Aviation, Inc.), variants of these powerplants were developed for the Air Force's Thor and Atlas missiles, and for the Army's Redstone and Jupiter rockets. The rocket engines for the latter played a highly significant role in the evolution of the Saturn vehicles.¹¹

In the early postwar era, while the Air Force developed cruise missiles, the Army generated an increasing expertise in liquid propulsion rocketry through special projects at the White Sands Proving Ground in New Mexico. At White Sands, von Braun and the rocketry experts from Peenemuende not only made lasting contributions to American ballistic missile capabilities but made early ventures into space exploration. Besides test firing a series of captured V-2 rockets for the Army's operational experience, the German experts helped coordinate a series of upper atmospheric research probes. One such project, known as the Bumper Series, employed a V-2 as the first stage with a Wac Corporal upper stage, one of which reached an altitude of 393 kilometers. In 1950, the last two Bumper launches took place in Florida, at the Long Range Proving Ground, located at Cape Canaveral—a prelude to U.S. space launches of the future. Another major activity included the Hermes program and involved the General Electric Company's working with the von Braun team under Army Ordnance cognizance. During Hermes operations, the basic V-2 rocket underwent successive modifications, increasing its performance envelope and payload capabilities, while giving the American contractors progressive experience in rocket technology. A number of more-or-less indigenous American vehicles were also flown. Although none became operational, they afforded a highly useful exposure to rocket development for government and contractor agencies alike, and one of the concepts, Hermes C-1, contributed directly to the development of the first significant American ballistic missile, the Army's Redstone.¹²

As the 1940s drew to a close, the Army decided to establish a new center of rocket activity. Although White Sands remained active as a test range, a facility devoted to basic research and prototype hardware development was needed. A site selection team finally settled on Redstone Arsenal in Huntsville, Alabama. Established in 1941 for the production of various chemical compounds and pyrotechnic devices (including small

CONCEPTS AND ORIGINS

solid-fuel rockets), Redstone had all the necessary attributes: shops, laboratories, assembly areas, and ample surrounding land to ensure both security and space for static-firing tests. Moreover, it was accessible to the Long Range Proving Ground, a rocket launch area of growing significance at Cape Canaveral. The transfer of von Braun's work from Fort Bliss was approved, and the Ordnance Guided Missile Center was in operation in Huntsville by the close of 1950.

During the Korean War, the new research center was assigned the development of a surface-to-surface ballistic missile with a range of 160 kilometers. A propulsion system adapted from the Navaho program enhanced rapid development, and the first launch of the new Redstone occurred at Cape Canaveral on 20 August 1953. Before declaring it operational in 1958, the von Braun team fired 36 more test vehicles. The prolonged Redstone development program epitomized the thorough, step-by-step engineering conservatism developed during the early years of rocket development at Peenemuende. This conservatism was a continuing trait of the von Braun team throughout the evolution of the Saturn program. Another point of significance concerned the involvement of the Chrysler Corporation as the prime contractor who built the last 20 R&D models and continued production of the operational models. The Chrysler connection provided valuable experience in government-contractor relationships that was the keynote of the development of the Saturn series of launch vehicles, and Chrysler, like Rocketdyne, also became an important contractor in the Saturn program.

In the meantime, the accumulated design experience of the Redstone program contributed to a joint Army-Navy development program involving the Jupiter vehicle, a direct derivative of the Redstone. This short-lived but interesting cooperation had its origins in the immediate postwar era. Because the Navy had its own interests in rocket technology and the Army possessed a reasonable supply of V-2 rockets, the two services collaborated in experimental V-2 launches from the flight deck of the aircraft carrier *Midway* in 1947. At an altitude of 1500 meters above the carrier's deck, a missile disintegrated in a ball of flame and debris. The specter of catastrophe, if such a large liquid-fueled rocket accidentally exploded on a ship at sea and spewed its huge volume of volatile propellants everywhere, led the Navy to proceed cautiously with liquid-propellant rockets. Nevertheless, the Department of Defense encouraged the formation of the joint Army-Navy venture in ballistic missiles in 1955, and the Army's designated organization in the partnership was the Army Ballistic Missile Agency (ABMA), created in 1956 and staffed primarily out of von Braun's group at the Redstone Arsenal. Major General John B. Medaris became ABMA's commanding officer. Wise in the ways of military bureaucracy, the enterprising Medaris also won unusually wide latitude in determining the direction of ABMA's research and allocation

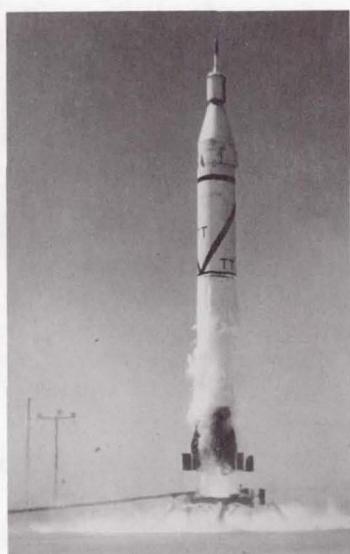
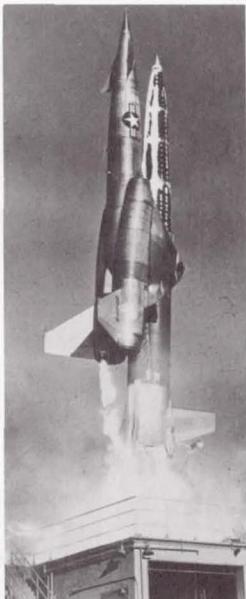
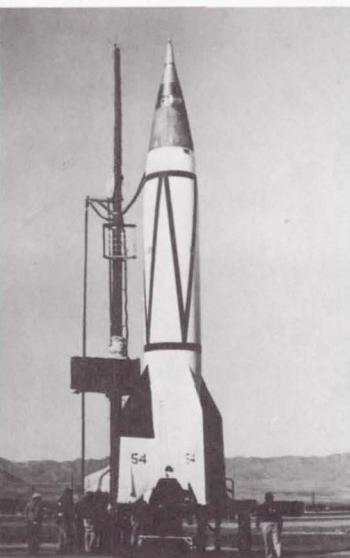
STAGES TO SATURN

of funds. Medaris and the equally venturesome von Braun made ABMA a remarkably resourceful and aggressive organization, especially when ABMA found itself in a solo role in Jupiter's eventual development.

This situation came late in 1956, when naval experts decided to concentrate on solid-fuel rockets. This direction eliminated logistic and operational difficulties inherent in the deployment of liquid-propellant rockets in seaborne operations, particularly with missiles launched underwater from submarines. The Navy gave official authorization to its own strategic missile—the Polaris—early in 1957. Based on a solid-fuel motor, the Polaris nevertheless borrowed from the Jupiter program in the form of its guidance system, evolved from the prior collaboration of ABMA and the Navy.

ABMA continued Jupiter development into a successful intermediate range ballistic missile (IRBM), even though the Army eventually had to surrender its operational deployment to the Air Force when a Department of Defense directive late in 1956 restricted the Army to missiles with a range of 320 kilometers or less. Even so, ABMA maintained a role in Jupiter R&D, including high-altitude launches that added to ABMA's understanding of rocket vehicle operations in the near-Earth space environment. It was knowledge that paid handsome dividends later.

Rockets of the 1950s: left to right: a captured German V-2 is readied for firing at White Sands, New Mexico; an Air Force Navaho is launched from the Air Force Missile Test Center, Florida; an Army Jupiter C is launched from the missile center with an Explorer satellite; Vanguard I is launched on a Vanguard booster from the Atlantic Missile Range.



CONCEPTS AND ORIGINS

SATELLITES, THE SPACE RACE, AND THE BOOSTER GAP

During the early 1950s, the Atomic Energy Commission successfully perfected smaller hydrogen-bomb warheads. In the Air Force, these warheads caused cruise missile development to be replaced by new emphasis on the Thor IRBM and the longer range missiles such as the Atlas intercontinental ballistic missile (ICBM). Successful launches of the single-stage Thor and the one-and-a-half-stage Atlas occurred in 1957 and 1958, and the Air Force also began work on an advanced ICBM, the Titan, a two-stage vehicle launched for the first time in 1959. The increasing payload capability of these various missiles opened the possibility of replacing their warheads with satellites and using them as boosters to launch heavy scientific payloads into space. The United States had already applied the growing expertise of rocket technology to the development of a family of sounding rockets to carry instrumentation for upper atmospheric research, such as the Navy's Aerobee and the Viking, which would reach altitudes between 160 and 320 kilometers. During the period of the International Geophysical Year 1957–1958, many nations around the world conducted a coordinated program of sounding rocket launches, including 210 sent up by the United States and 125 launched by the Soviet Union. However, the United States had an even more ambitious goal than launching sounding rockets during the International Geophysical Year. America planned to orbit its first small satellite.

The satellite project began in 1955. In spite of the international spirit of cooperation inherent in International Geophysical Year programs, a strong sentiment in the United States was that America should not waste time and should attempt to orbit a satellite ahead of the Russians. For the booster, a blue-ribbon selection panel from military and industry analyzed a list of candidates that included the Atlas, the Redstone, and the Viking. ABMA argued that Atlas was still untested in 1955. The Viking vehicle, its opponents noted, still required a program to uprate its first-stage engines and develop new second and third stages before it could become operational. On the other hand, the Army's Jupiter C vehicle—a direct derivative of the proven Redstone—appeared to have all the capabilities necessary to launch a satellite successfully. For complex reasons, the committee selected the Viking; they argued that the Viking had been intended from the start as a vehicle for space research and that its development would not impinge on America's ballistic missile program, which was considered to be lagging behind the Russians' program. The choice of Viking, in the context of Cold War concerns over international prestige and technological leadership, was a controversial decision. The new program, to be known as Project Vanguard, was authorized in September 1955 under the Department of the Navy.¹³

STAGES TO SATURN

Although the first stage was successfully launched on 23 October 1957, the first Vanguard with three "live" stages blew apart on the pad, and its successor veered off course and disintegrated before it had ascended six kilometers. As if these last two fiascos were not enough, Vanguard was already overtaken by events. The Russians had orbited *Sputnik I* on 4 October 1957. Within four weeks the Soviet Union demonstrated that Sputnik was no fluke by launching a second orbital payload; *Sputnik II*, carrying the dog "Laika," went into orbit on 3 November.¹⁴ The potent Russian boosters threw a long shadow over Vanguard. Plans to use an existing military booster gained support once again.

The honor of launching America's first satellite fell to the close-knit group of pioneers who had dreamed of space exploration for so many years, the von Braun team. When the Army's Redstone-Jupiter candidate for the International Geophysical Year satellite was rejected, ABMA assumed a low profile but kept up work. As one ABMA insider explained, von Braun found a "diplomatic solution" to sustain development of the Jupiter C by testing nose cones for the reentry of warheads. Following launch, solid-propellant motors in the second and third stages accelerated an inert fourth stage attached to an experimental nose cone. The nose cones tested ablative protection as they reentered Earth's atmosphere. After successful tests during the summer of 1957, von Braun declared that a live fourth stage and a different trajectory would have given the United States its orbiter. In any case, ABMA was not unprepared to put an American payload into Earth orbit. Slightly more than four weeks after the launch of Sputnik, the Secretary of Defense finally acceded to persuasive pleas from ABMA to put up an artificial satellite, using its own vehicle. Authorization from the secretary for two satellite launches came on 8 November 1957, and the initial launch was set for 30 January 1958. ABMA missed the target date by only one day, when a Jupiter C orbited *Explorer I* on 31 January 1958.¹⁵ The unqualified success of *Explorer I* and its successors derived in large part from the existing operational capability of the Jupiter C launch vehicle, from the flexibility of ABMA's in-house capability, and from the technical expertise of the Jet Propulsion Laboratory (JPL), which functioned administratively as a unit of the California Institute of Technology and got a large share of its funds through Army contracts. JPL developed the solid-fuel propulsion units for the upper stages of the Jupiter C as well as the payloads for the Explorer satellite. Within the next few months, the Jupiter C vehicles, designated as Juno boosters for space launches, also carried payloads into orbit around the moon and the sun.¹⁶

During the public consternation and political turmoil in the wake of the Soviet space spectaculars, the American government began a thorough reappraisal of its space program. One result was the establishment of the National Aeronautics and Space Administration (NASA) in place

CONCEPTS AND ORIGINS

of the old National Advisory Committee for Aeronautics (NACA). Created when President Eisenhower signed the National Aeronautics and Space Act into law on 29 July 1958, NASA was organized to ensure strong civil involvement in space research so that space exploration would be undertaken for peaceful purposes as well as for defense. Although late in success, Project Vanguard was not without its benefits. *Vanguard I* finally got into orbit on 17 March 1958, and two more Vanguards attained orbit in 1959. The program yielded important scientific results, as well as valuable operational experience. Upper stages of the Vanguard vehicle were used in conjunction with later booster vehicles such as the Thor and the Atlas, and the technique of gimbaled (movable) engines for directional control was adapted to other rockets.¹⁷

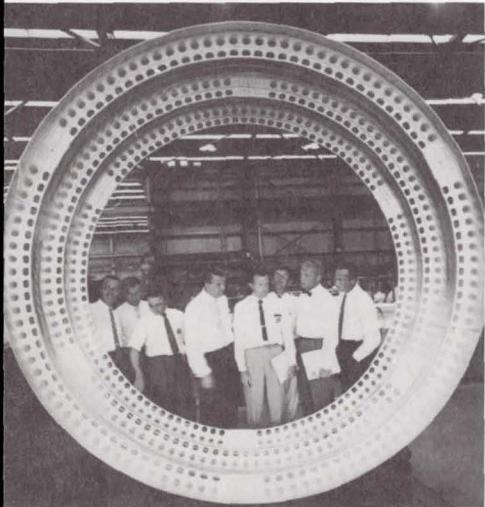
The period 1958–1959 seemed to trigger feverish activity in space exploration. In the months and years that followed, dozens of satellites and space vehicles were launched, including space probes that landed on Venus and the moon. Although other nations inaugurated space programs and launched their own boosters and scientific payloads, most public attention fastened on the manned “space race” between the U.S.S.R. and the United States. Within the first week of NASA’s existence in October 1958, Project Mercury was authorized to put an American astronaut into orbit, and the space agency began negotiations to obtain the necessary boosters and select candidates for astronaut training.

At that time, NASA did not have the resources to develop its own boosters for space exploration. Mission planners reached into the inventory of American ballistic missiles and finalized agreements with the Army and ABMA for use of the Redstone, as well as the Atlas ICBM to be acquired from the Air Force. To check out requirements and systems for manned orbital operations, NASA planned to employ the Redstone for suborbital launches, and the more powerful Atlas would be used for the orbital missions. Selection of the first seven Mercury astronauts was announced in the spring of 1959, and work proceeded on the development and testing of the Mercury space capsule, including unmanned test launches in 1960. Early in 1961 a Mercury-Redstone launch from Cape Canaveral carried the chimpanzee “Ham” over 640 kilometers down-range in an arching trajectory that reached a peak of 253 kilometers above Earth. The chimp’s successful flight and recovery confirmed the soundness of the Mercury-Redstone systems and set the stage for a suborbital flight by an American astronaut. But the Americans were again upstaged by the Russians.

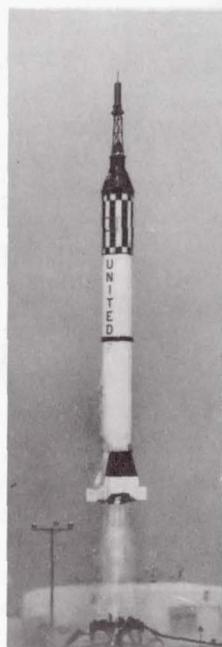
On 12 April 1961, Major Yuri Gagarin was launched aboard *Vostok I* and completed one full orbit to become the first human being to travel in orbit about the Earth. Just as the Russians appeared to have overtaken the Americans in the area of unmanned space projects, they now seemed to have forged ahead in manned exploration as well. Although Alan B. Shepard made a successful suborbital flight atop ABMA’s Redstone

STAGES TO SATURN

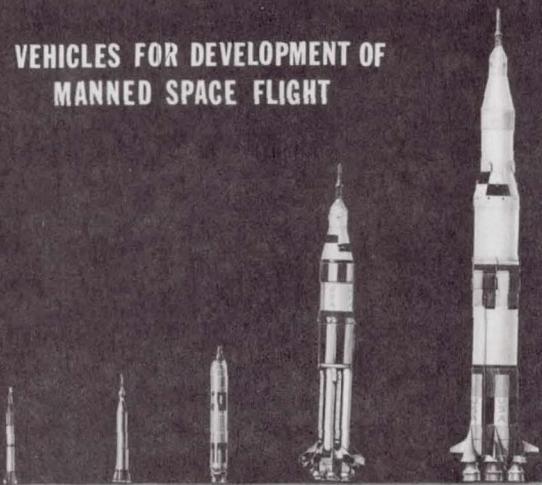
booster on 5 May, even this milestone was overshadowed when Soviet Cosmonaut Gherman Titov roared into space aboard *Vostok II* on 6 August and stayed aloft for 17½ orbits. It was not until the following year that Astronaut John H. Glenn became the first American to orbit the Earth. Boosted by a modified Atlas ICBM, *Friendship 7* lifted off from Cape Canaveral on 20 February 1962 and orbited the Earth three times before Glenn rode the capsule to splashdown and recovery in the Atlantic.



At the Marshall Space Flight Center (left), Dr. Wernher von Braun is flanked by the seven original astronauts as he explains details of rocket fabrication. At right, a Mercury-Redstone rocket launches Astronaut Alan B. Shepard on this nation's first manned space flight. Below, the manned flight vehicles are shown in scale.



**VEHICLES FOR DEVELOPMENT OF
MANNED SPACE FLIGHT**



REDSTONE ATLAS TITAN II SATURN IB SATURN V

MERCURY

GEMINI

APOLLO

CONCEPTS AND ORIGINS

These and other manned flights proved that humans could safely travel and perform various tasks in the hostile environment of space. Over the next few years, both Russian and American manned programs improved and refined booster and spacecraft systems, including multicrew missions. The Russians again led the way in such missions with the flight of *Voshkod I* in 1964 (a three-man crew), and a Russian cosmonaut Aleksey Leonov performed the first "space walk" during the *Voshkod II* mission in 1965. The same year, NASA began its own series of two-man launches with the Gemini program. With a modified Titan II ICBM as the booster, the first Gemini mission blasted off from Cape Kennedy on 23 March 1965, and the Gemini program, which continued into the winter of 1966, included the first American space walks, as well as highly important rendezvous and docking techniques. The maneuvers required to bring two separate orbiting spacecraft to a point of rendezvous, followed by the docking maneuver, helped pave the way for more ambitious manned space missions. Plans for multimanned space stations and lunar exploration vehicles depended on these rendezvous and docking techniques, as well as the ability of astronauts to perform certain tasks outside the protected environment of the spacecraft itself. The successive flights of the Mercury-Redstone, Mercury-Atlas, and Gemini-Titan missions were progressive elements in a grand design to launch a circumlunar mission to the moon and return to the Earth.¹⁸

Against the background of Mercury and Gemini developments, work was already progressing on the Apollo-Saturn program. The spacecraft for the Apollo adventure evolved out of the Mercury and Gemini capsule hardware, and other research and development was directed toward new technology required for a lunar lander and associated systems. A parallel effort involved the development of an entirely different family of boosters. Heretofore, NASA had relied on existing boosters requisitioned from the armed services—the Redstone missile, along with Thor, Atlas, and Titan. For manned lunar missions, a rocket of unusual thrust and lifting capacity was called for—literally, a giant of a booster. During 1960, the von Braun team was transferred from ABMA to NASA, bringing not only its conceptual understanding of manned space flight (based on preliminary studies in 1957 and 1959) but also its acknowledged skills in the development of rockets. For manned missions, the von Braun team developed a totally different big booster—the Saturn.

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III

The Saturn Building Blocks

The original impetus for Saturn envisioned a brawny booster to launch Department of Defense payloads. The von Braun team at the Army Ballistic Missile Agency (ABMA) received money from the Department of Defense's Advanced Research Projects Agency to demonstrate the concept. Furthermore, von Braun's group eventually became the nucleus of NASA's Marshall Space Flight Center (MSFC). These convolutions and the vague outlines of evolving Saturn vehicle technology constitute the themes of chapter 2.

The Saturn program eventually included three basic vehicles: Saturn I, Saturn IB, and Saturn V. Chapter 3 describes the events that led to these three separate rockets, whose configuration evolved out of the choice to go the moon by means of the lunar orbit rendezvous technique. MSFC began development of facilities to develop and test the mammoth boosters. Chapter 3 concludes with a discussion of the design and manufacture of lower-stage boosters for the Saturn I and Saturn IB.

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2

Aerospace Alphabet: ABMA, ARPA, MSFC

In November 1956, when the Air Force finally triumphed over the Army and Navy for leadership in long-range military rockets, planners at ABMA momentarily regrouped to plot a new direction, a strategy for large booster development geared instead to the exploration of space. Having lost round one to the Air Force, ABMA's stratagem was to leapfrog onward and upward to a quantum jump.¹

In April 1957, ABMA began design studies on an advanced booster concept. With a total thrust of approximately 6 800 000 newtons (1.5 million pounds) in the first stage alone, the proposed vehicle was referred to as the Super-Jupiter. The impetus for the development of a Super-Jupiter class apparently evolved from Department of Defense plans for "certain advanced missions using space devices in communication," as well as space probes and weather satellites. However, such payloads, especially satellite programs, required a booster much larger than existing launch vehicles. The Department of Defense guidelines called for a launch vehicle capable of putting 9000 to 18 000 kilograms into Earth orbit or accelerating space probes of 2700 to 5400 kilograms to escape velocity. At that time, ABMA estimated that satellite carriers on order, such as Thor, Juno II, and Atlas, could be expected to put up to 1400 kilograms into orbit. This capability might be increased to 4500 kilograms with high-energy propellants in upper stages. However, these boosters, with conventional propellants, would not be available for at least two years. The high-energy versions would not be operational until 1961 or 1962. Given the urgency of Department of Defense requirements for large payloads, a new class of booster and associated equipment had to be developed in a very short time, while keeping costs within low DOD limitations.²

STAGES TO SATURN

ARPA'S BIG BOOSTER

Early design and cost studies at ABMA suggested the possibility of using a single engine of 4 450 000 newtons (1 million pounds) of thrust, for which Rocketdyne Division of North American had made a feasibility study for the Air Force. Although this was an "Air Force engine," no other large propulsion system existed. The F-1 engine seemed unlikely to reach the point of full-scale testing for at least two years—too late to meet the accelerated booster development program of the Department of Defense. In any case, a booster with 6 700 000 newtons (1.5 million pounds) of thrust was needed, so the ABMA planning staff gave up on the simplicity of one large engine and turned to a combination of four smaller ones.

Rocketdyne also had a project under way for a 1 600 000- to 1 690 000-newton (360 000- to 380 000-pound) thrust engine known as the E-1. Proposals for the four-engine booster involved the use of what one ABMA official called "off-the-shelf tankage" (presumably a single large-diameter booster propellant tank from the existing stable of military missiles) with the four E-1 engines in a cluster underneath it. This version of Super-Jupiter was closely analyzed by ABMA and technical experts from North American, and a number of upper-stage configurations were suggested. With specific choices in terms of engines and tankage still open, ABMA was by now certain that the clustering of engines was the most feasible route to attain quickly the Department of Defense goal of a 6 700 000-newton (1.5-million-pound) first-stage booster. In December 1957, ABMA delivered its proposal to the Department of Defense: "A National Integrated Missile and Space Vehicle Development Program." The document affirmed the clustered engine mode as a shortcut method to achieve large payload capability in the least amount of time.³

Nevertheless, Super-Jupiter still remained a feasibility study, existing only on paper and within the fertile imaginations of von Braun and his group at Huntsville. The Department of Defense had its stated requirements for payloads of many tons, and ABMA had its proposals for possible booster configurations, but there was still no priority or money to get Super-Jupiter past the level of paperwork. The immediate catalyst came in the form of a new Department of Defense organization whose high-priority recommendations cut through layers of red tape and allocated dollars for converting studies into hardware—the Advanced Research Projects Agency (ARPA).

During the turbulent months of late 1957 and early 1958, the Eisenhower administration wrestled with the challenges posed by *Sputnik I*, the abortive launches of Vanguard, and the last ditch mission of *Explorer I*. A long-term, reasoned, and integrated space program called

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

for some informed and firm decisions. In February, President Eisenhower chartered a special committee under the guidance of Dr. J. R. Killian to study the issues and make recommendations for a national space program. As the Killian committee convened, the Department of Defense moved on its own to rationalize space research involving the armed services. On 7 February 1958, ARPA was formally established by Secretary of Defense Neil H. McElroy, and after part-time guidance through most of two months, Roy W. Johnson became the new agency's director on 1 April. Johnson, a graduate of the University of Michigan, had been executive vice-president at General Electric. There was no doubt that Johnson had extensive authority: he reported directly to the Secretary of Defense. The influence of ARPA became evident when William M. Holaday, Director of Guided Missiles in the Department of Defense, received orders to transfer some of his activities to the new agency. Johnson insisted on running ARPA as a mechanism for establishing goals and coordinating research efforts, as opposed to active R&D work and management of contracts. ARPA made top decisions and allocated the money, giving full rein to whatever organization was nominated to run a project. ARPA remained a small, tightly knit organization, numbering about 80 people "including the girls (in the office)," as Johnson put it, and drew the core of its technical staff from specialists in the Army, Navy, and Air Force.⁴

Through the spring of 1958, ARPA began to get its own organization in line while ABMA continued its preliminary studies for the Super-Jupiter with E-1 engines. Then in July, ARPA began to show more specific interest in the huge 6 700 000-newton (1.5-million-pound) booster but argued for the use of available engine hardware, as opposed to the still untried E-1 propulsion systems. ARPA's line of reasoning was tied to its objective of developing the big booster in the shortest amount of time and doing the job within a framework of limited funds. The von Braun group in Huntsville possessed considerable experience with the engines for its own Jupiter series of rockets, and so a new cluster, with eight Jupiter engines instead of four E-1 types, began to evolve. Even though no formal agreements existed as yet between ARPA and ABMA, the close working relationship between the two organizations was evident in the name chosen for the new eight-engine booster. Known as Juno V, the designation followed ABMA's prior conceptual studies for advanced Juno III and Juno IV multistage rockets. By using off-the-shelf hardware, including the engines, it was estimated that Juno V, compared with the Super-Jupiter with E-1 engines, would save about \$60 million and as much as two years research and development time.⁵

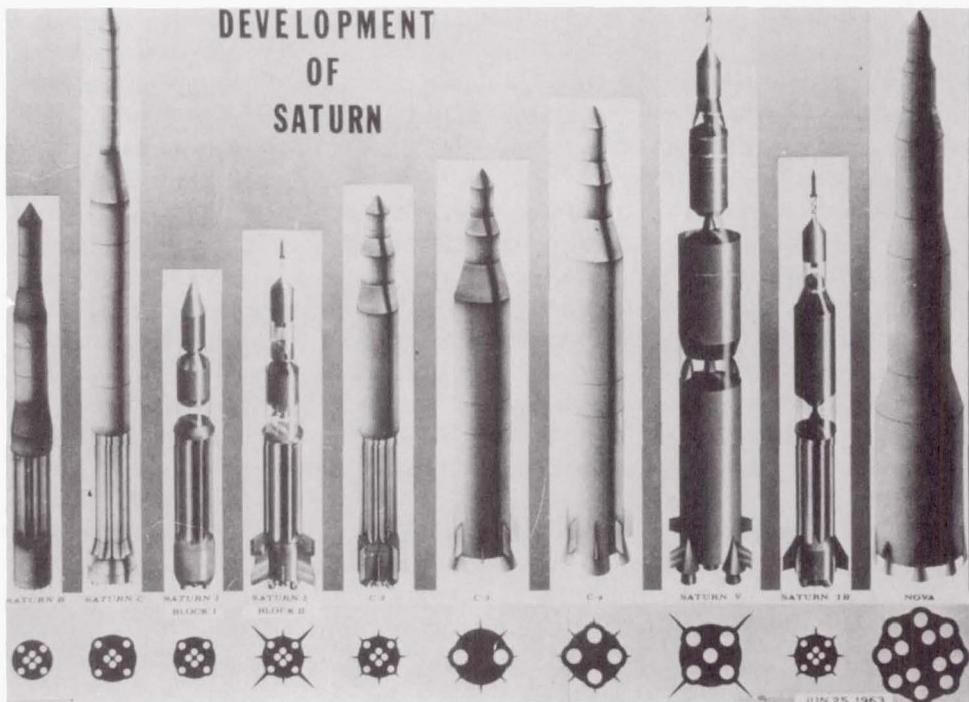
With such preliminaries out of the way, ARPA issued more specific instructions to ABMA, granting authority and authorizing funds for the Juno V. ARPA Order Number 14-59, dated 15 August 1958, clarified the discussions of the previous weeks:

STAGES TO SATURN

Initiate a development program to provide a large space vehicle booster of approximately 1 500 000-lb. [6 700 000-newton] thrust based on a cluster of available rocket engines. The immediate goal of this program is to demonstrate a full-scale captive dynamic firing by the end of CY 1959.

This was a historic document, for it committed money and engaged the von Braun team at Huntsville in an effort they had long dreamed about. Juno V became the progenitor of a new family of launch vehicles that would be used in the nation's future space program. As von Braun himself put it, "Juno V was, in fact, an infant Saturn."⁶

Indeed, during this early period the Saturn designation was frequently used by von Braun and others inside ABMA. A new name seemed appropriate, because Saturn was seen as a distinct break from the Juno series—a new breed of launch vehicle that would see an active lifetime of a decade or more. "The SATURN," observed one ABMA report, "is considered to be the first real space vehicle as the Douglas DC-3 was the first real airliner and durable work-horse in aeronautics."⁷ In the autumn of 1958, however, the full development of the Saturn was only beginning. As two engineers from Huntsville commented, "The state of the art at this time classified the Saturn booster as almost impossibly complex."⁸



AEROSPACE ALPHABET: ABMA, ARPA, MSFC

The decision not to use the E-1 engine and to go to off-the-shelf hardware did not catch ABMA personnel flatfooted. Technicians and engineers at Huntsville were already working on propulsion systems related to the Jupiter to increase thrust, simplify operation, and improve overall mechanical and other systems. This work gave the engine development an important momentum early in the game and encouraged ABMA's optimism when ARPA requested a program for static firing a multiple engine cluster within 18 months, while operating on a shoestring budget. Still, "it was not easy," Willy Mrazek, one of the top ABMA planners, mused years later. One of the problems involved the engine manufacturer. When ABMA contacted Rocketdyne and laid out the program, company officials were intrigued by the big cluster idea but protested that the dollar allocation simply could not stretch far enough to finance the rebuilding and testing of engines and spares for the size of the program suggested by ABMA. By using all their persuasive power, and even a little "arm twisting," as Mrazek recalled, the von Braun group convinced Rocketdyne to take the plunge, including the authorization for the company to glean hardware from their stockrooms that was left over from prior manufacturing and development programs sponsored by the government. By 11 September 1958, Rocketdyne had signed a contract with ABMA to uprate the original Thor-Jupiter engine, known as the S-3D propulsion system, creating a unit suitably modified to operate in the cluster configuration. The new engine was called the H-1, and ABMA signed away half of its available funds to get it.⁹

With the money they had left, ABMA went to work in Huntsville to decide how to allocate their scarce dollars for oversized test stands and to define the configuration of the tankage. An early decision was made to modify an existing test stand "out in our backyard," as Mrazek phrased it, keeping in mind that, although it had been designed to take Army missiles like the Jupiter 2.67-meter-diameter tank and a thrust of 734 000 newtons (165 000 pounds) the test stand had to be reworked to take a "monster" that was 24 meters high, 6 meters in diameter, and built to put out a thrust of almost 6 700 000 newtons (1.5 million pounds). The lean budget also had to cover a miscellany of items such as tooling to fabricate the oversized tanks and development of a thrust structure to take the maximum force of eight engines firing together at full throttle. There was also the need for oversized assembly jigs for manufacturing and checkout of the big new booster and for the costs of getting all the materials and the manpower to put the thing together. Like Rocketdyne, ABMA found that short funds made a virtue of scrounging in the dark corners of warehouses and stockrooms and put a premium on imaginative shortcuts.

Because ARPA Order Number 14-59 called only for a static demonstration in the test stand, not a flight-configured launch vehicle, the booster that began to take shape on the Redstone Arsenal drawing

STAGES TO SATURN

boards and in the shops was definitely a bargain-basement and patch-work affair. The volume of the tankage posed a special problem. The fabrication and welding of a single 6-meter-diameter tank, with separate compartments for fuel and oxidizer, meant new techniques and working jigs. Consumption of time and money threatened to become exorbitant. A different approach to the problem evolved, and existing tanks were used instead. From its own earlier production runs, ABMA located partial rejects and incomplete 1.78-meter tanks from the Redstone and 2.67-meter tanks from the Jupiter missiles. Since the engines were going to be clustered, why not the tanks? "The dire need made us more inventive," Mrazek pointed out, "and we bundled the containers to be loaded with propellants." So the vaunted big booster emerged from the drawing boards as a weird compromise of eight separate 1.78-meter Redstone tanks surrounding a 2.67-meter Jupiter tank. It did not look exactly like a smooth, streamlined futuristic vehicle for the exploration of space, nor was it intended to be. Designed solely to see if a blockbuster of a rocket could run its eight engines in concert, ABMA was satisfied with its awkward-looking compromise.¹⁰

While the work in Huntsville progressed, representatives from ARPA kept a close watch on the proceedings and made frequent visits to Redstone Arsenal. They increasingly liked what they saw. So much so, in fact, that they decided to propose a series of test flights. On 23 September 1958, ARPA and the Army Ordnance Missile Command (AOMC) drew up an additional memorandum of agreement enlarging the scope of the

A 1959 version of Saturn I is shown at the right. Redstone and Jupiter tankage (left) were combined in Saturn I's first stage.



AEROSPACE ALPHABET: ABMA, ARPA, MSFC

booster program. Signed by Major General J. B. Medaris for AOMC and Roy Johnson for ARPA, the joint memorandum stated: "In addition to the captive dynamic firing . . . , it is hereby agreed that this program should now be extended to provide for a propulsion flight test of this booster by approximately September 1960." Further, the von Braun group was called on to produce three additional boosters, the last two of which would be "capable of placing limited payloads in orbit." Along with the new scheme came much needed funds. ABMA could now count on \$13.4 million in FY 1959 and \$20.3 million in FY 1960 for the captive firing test and first launch, in addition to \$8.6 million in the same period for development of appropriate facilities. For the three additional flights by 1961, ABMA would receive as much as \$25 million to \$30 million.

The decision to make the Juno V into a flight vehicle added new dimensions to planning problems. First, a launch site had to be selected. Moreover, the size of the booster posed unique transportation problems. As long as the launch location remained undetermined (possibly a remote site in the Pacific), ABMA planned to dismantle the entire booster and airlift the components separately, a concept that would be possible because of the use of individual propellant tanks, engines, and associated structural modules. Still, the Juno V engineering team was never quite sure the dismantling and rebuilding scheme would work effectively. "Thank goodness," Mrazek admitted, "we never had to disassemble the first flight vehicle." In the end, it was agreed to launch from the Atlantic Missile Range at Cape Canaveral, and ABMA worked out a more feasible method of transporting its launch vehicles intact by relying on water routes.¹¹

FROM NACA TO NASA

While ARPA proceeded to hammer out a program for booster development, a number of government committees were at work, attempting to clarify overall priorities for a national space program. On the heels of Sputnik, Senator Lyndon B. Johnson began probing the status of America's national security and the space program through hearings of the Senate Preparedness Investigation Subcommittee of the Senate Armed Forces Committee. As chairman of the subcommittee, Johnson kicked off the hearings on 25 November 1957. The National Advisory Committee for Aeronautics (NACA) was gearing up its own studies about the same time, and the White House also had a high-powered study in progress—the Killian committee, directed by President Eisenhower's recently appointed Special Assistant for Science and Technology, James R. Killian. The subcommittees of Killian's group reporting early in 1958 evidently had the most influence in shaping the Administration's approach. Even though the committee reports were shot through with overtones of

STAGES TO SATURN

national security and the notion of a space race with the Russians, Administration officials generally agreed that proposals for a new space agency should result in an organization that was essentially nonmilitary. Because of its civil heritage, existing programs, and general programs, NACA was singled out as the most likely candidate to form the nucleus, though a new name was recommended. Strictly military programs would continue under the Department of Defense.¹²

During April 1958, Eisenhower delivered the formal executive message about the national space program to Congress and submitted the Administration's bill to create what was then called the "National Aeronautical and Space Agency." The hearings and committee work that followed inevitably entailed revisions and rewording, but the idea of a civilian space agency persisted, and the old NACA role of research alone began to change to a new context of large-scale development, management, and operations. Congress passed the National Aeronautics and Space Act of 1958 on 16 July, and Eisenhower signed the bill into law on the 29th. During August, the Senate speedily confirmed Eisenhower's nominations of T. Keith Glennan as Administrator and Hugh Dryden as Deputy Administrator. At the time of his appointment, Glennan was president of Case Institute of Technology and had been a member of the Atomic Energy Commission. Dryden, a career civil servant, had been Director of NACA but was passed over as the new chief of NASA. The subsequent days and months included some jockeying and horse trading to establish the principal directives of the new organization.

When the Space Act was signed, no mention was made as to the management of a program for manned space flight, and the Army, Navy, and Air Force continued to maneuver for position until late August,

President Dwight D. Eisenhower presents commissions as the first Administrator and Deputy Administrator of the new National Aeronautics and Space Administration to Dr. T. Keith Glennan (right) and Dr. Hugh Dryden.



AEROSPACE ALPHABET: ABMA, ARPA, MSFC

when Eisenhower specifically designated NASA as the agency to conduct manned space flight programs. In September, NASA's new Administrator, T. Keith Glennan, and Roy Johnson of ARPA agreed to cooperate in the development of a manned satellite. NASA's effective date of birth was 1 October 1958. The employees who left their NACA offices Tuesday evening, 30 September, returned to the same offices Wednesday morning as personnel of the National Aeronautics and Space Administration. With the passage of time, ARPA's entire big-booster program would find a niche in the new organization.¹³ These were bold plans, and neither the old NACA nor the new NASA possessed an existing capability for the job. Glennan wanted ABMA's von Braun team for its abilities in launch vehicles and the Jet Propulsion Laboratory (a major Army contractor) for its general expertise in astronautical engineering and payload development. NASA had to accept a compromise: the space agency got the Jet Propulsion Laboratory (officially transferred on 3 December 1958), but ABMA's missile team stayed in the Army. ABMA and its big booster were, however, already enmeshed in NASA planning, and it was only a matter of time before assimilation was complete.¹⁴

NACA, for its part, had already been speculating about its role in the space program, and several committees had been at work in late 1957 and early 1958 studying the various factors a space program entailed: vehicles; reentry; range, launch, and tracking; instrumentation; space surveillance; human factors; and training. Late in March 1958, a NACA group studying "Suggestions for a Space Program" included notations for a launch program in January 1959 to put satellites of 135 000 to 225 000 kilograms in orbit (reflecting the earlier Department of Defense plans), and development of a rocket of 4 450 000 newtons (1 million pounds) thrust, as well as "development of hydrogen fluorine and other special rockets for second and third stages."

The ABMA large booster program first entered NASA planning through the NACA Special Committee on Space Technology chaired by Guyford Stever. The Working Group on Vehicular Program included von Braun as chairman. Organized 12 January 1958, the Stever committee made its final report on 28 October, when NASA was already a month old.¹⁵ Von Braun's working group on vehicles had already made its preliminary report on 18 July. The language did not differ much from that of the final draft. The report began with harsh criticism of duplication of effort and lack of coordination among various organizations working on the nation's space programs. "The record shows emphatically," the report said, that the Soviet Union was definitely ahead of the United States in space travel and space warfare.

How was the United States to catch up? There were several existing vehicle systems to help the United States proceed on a logical and consistent space research program. At least two large booster types under

STAGES TO SATURN

development or in the planning stages would place the Americans in a better position. The von Braun paper described five generations of boosters. First was the Vanguard class of launch vehicles, and second were the Juno and Thor IRBM vehicles. Third were the Titan and Atlas boosters from the ICBM inventory. Fourth came the clustered boosters, which would yield up to 6 700 000 newtons (1.5 million pounds) of thrust. Fifth, and last, was the possibility of using an advanced 6 700 000-newton (1.5-million-pound) thrust single-barrel engine in a cluster of two to four engines to give up to 25 000 000 newtons (6 million pounds) of thrust. How were they to be employed? The working group conjectured that the United States might put into operation a four-man space station in 1961 with the use of the ICBM boosters. By using clustered boosters, with first flights beginning in 1961, the committee estimated a manned lunar landing in 1965–1966. The clustered vehicles would also support the deployment of a 50-man space station in 1967, and the fifth generation of boosters would support sizable moon exploration expeditions in 1972, set up a permanent moon base in 1973–1974, and launch manned interplanetary trips in 1977. “The milestones listed . . . are considered feasible and obtainable as indicated by the supporting information presented in the body of the report,” the working group concluded.¹⁶

The recommendations to achieve these goals included NASA’s rapid development as the major director and coordinator of the vehicle program, working in partnership with ARPA. “The immediate initiation of a development program for a large booster, in the 1.5 million pound [6 700 000 newton] thrust class, is considered a key to the success of the proposed program,” the report stated, and urged the development of such an engine. The program would cost about \$17.21 billion to pay for 1823 launches, including the as-yet undeveloped ICBM and clustered boosters. There would be considerable savings, the group noted, if a comprehensive booster recovery scheme were incorporated.¹⁷

With von Braun representing ABMA on the Stever committee, his presence marked an early meshing of ABMA and NACA in the nation’s space programs. Indeed, the Stever committee was intended to fill in the gaps in NACA space technology. NACA officials James Doolittle, Dryden, and Stever selected committee members with an eye to their future roles in the space programs as well as educating NACA personnel in space R&D. Large rocket boosters certainly constituted a big gap in NACA competence, so that the selection of von Braun was a key move, along with Sam Hoffman of Rocketdyne, Abe Hyatt of the Office of Naval Research, and Colonel Norman Appold, representing Air Force General Bernard Schriever, who spearheaded the development of big rockets in the Air Force.¹⁸

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

SATURN PAYLOADS

The interwoven activities of a civilian space agency using a booster of military origins left the issue of payloads somewhat uncertain. ABMA had been operating its big booster program under the aegis of ARPA and considered the Juno V primarily a military vehicle with an imprecise potential for use in a civilian role. On 13 October 1958, ABMA listed its customers in order of importance. First was ARPA, as the Department of Defense representative of all military services, with the Juno V as a general carrier vehicle for research and development of "offensive and defensive space weapons." Certain specific tasks were forecast for each of the military services, including navigation satellites for the Navy; reconnaissance, communications, and meteorological satellites for the Army and Air Force; support for Air Force manned missions; and surface-to-surface supply for the Army at distances up to 6400 kilometers. For NASA, the ABMA planners considered the possibilities of the Juno V in support of satellites, space probes, and space stations, as well as a test bed for a 6 700 000-newton (1.5-million-pound) thrust engine and other propulsion systems. There was also conjecture about using the big clustered booster for international programs sponsored by the United Nations and for missions under contract to companies in the private sector.¹⁹

Because the mission plans were beginning to place more and more emphasis on putting payloads in orbit, there was an evident need for an upper stage to ensure orbital velocity of the payload. During the latter months of 1958, engineers at ABMA had already begun the search for a feasible upper stage for the Juno V, although the amended ARPA order in September called for lower flight stages only. Medaris urged upper-stage studies because he liked the idea of a unified and cohesive design effort; applying the "off-the-shelf" dictum, he sought to identify possible upper-stage candidates from projects already under way. One suggestion resulting from such brainstorming was to mount an X-15 research plane atop the Juno V, or perhaps incorporate an Air Force project known as Dyna-Soar. The X-15 idea did not last long, but Dyna-Soar persisted for several years. The Dyna-Soar (for dynamic soaring) dated from the autumn of 1957 and was envisioned as a manned, rocket-propelled glider in a delta-winged configuration, capable of reaching altitudes of up to 120 kilometers. More likely prospects for Juno V upper stages included Jupiter, Atlas, and Titan.²⁰

The problems of selecting the Juno V configuration, upper stages, and payloads also bothered the people at NASA. Sitting in his office on the second day of the new year 1959, W. L. Hjornevik, Assistant to the Administrator, dashed off a memo to his boss, Glennan. Hjornevik's

STAGES TO SATURN

message addressed itself to a basic issue in NASA's future: "Next Steps in the Development of a National Booster Program." The overtones in the memo suggested the uncertainties that still faced the young organization, not only in crystallizing specific goals but also in developing the capabilities for the tasks ahead. In spite of conversations with Dryden and others at NASA, Hjornevik wrote, he was still not sure of the proper route to take in developing a rational booster program. The payloads were still unsettled, and there was the problem of timing to bring boosters on line while the payload issue was still open. The question of a conventionally fueled second stage remained unanswered, even while "our position on the million-pound cluster" was unresolved.²¹

During 1959, NASA began to cope with these issues. A plethora of committees, long meetings, and voluminous reports provided the milieu in which NASA and Department of Defense personnel came to agreement on booster priorities, upper stages, and the issue of high-energy propellants. In the process of settling these problems, NASA acquired its own in-house capability for the production of the nation's first large launch vehicles, to be known as the Saturn rockets.

In a report prepared for President Eisenhower, dated 27 January 1959, NASA officially structured its own plan for a national space vehicle program. Attributed to NASA's propulsion staff, the document was prepared under the aegis of Abraham Hyatt, Chief of Launch Vehicles. The principal author was a NASA engineer, Milton Rosen. Preparation of the report included liaison with the Department of Defense, especially ARPA, the Air Force, and the Army to avoid duplication of effort and keep the Department of Defense informed of NASA's intentions regarding the use of military hardware. In its preamble, Rosen's report emphasized the lag in American rocket technology vis-à-vis the Russians and underscored the need for a new generation of large boosters. "The current group of booster vehicles, namely Vanguard, Jupiter C, Juno II, and Thor-Able, were all hurriedly assembled under pressure of meeting the threat of Russian Sputniks," the document declared, "and none of them possesses the design characteristics required by future needs of the National Space Program." A successful space program, in NASA's view, required three new classes of general-purpose launch vehicles.

The first type included two versions based on the Atlas, one as a single-stage booster, and the other as a two-stage booster using the liquid-hydrogen-fueled Centaur as the second stage. The Centaur proposal had special significance, because liquid hydrogen (LH_2) technology was recommended for inclusion in later designs. In fact, if high-energy liquid hydrogen fuel failed to become an operable technology, then the Rosen report predicated disappointingly low payloads in the future.

The second group of boosters was keyed to the Juno V, the ABMA eight-engine cluster concept. NASA envisioned the Juno V as the first stage of a large multistage vehicle, requiring second and third stages to

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

make a complete booster, and the report proposed two different configurations. For the version known as Juno V-A, the NASA propulsion staff recommended adding the Titan I ICBM, itself a two-stage missile with conventional fuel, making a three-stage vehicle. For Juno V-B, the third (top) stage would be replaced with an LH₂-fueled vehicle, probably the Centaur, to achieve higher escape velocities. Missions for the two Juno V variations included orbital research payloads, a five-man orbiting module, and unmanned lunar and other planetary missions using a fourth stage to gain escape velocity for larger payloads. The report further estimated that the Juno V configurations would be operational in 1963, with a useful lifetime of 5 to 10 years.

One of the most interesting items in the Rosen report pertained to a completely new class of launch vehicle—a super rocket of extraordinary size and payload capability known as Nova. Propulsion for the Nova class of vehicles would rely on the 6 700 000-newton (1.5-million-pound) thrust single-chamber engine that had been under development by the Air Force. With four engines clustered in the first stage, Nova would generate an unprecedented 25 000 000 newtons (6 million pounds) of thrust at liftoff. The second stage would use one of the same engines, and the third and fourth stages would incorporate liquid-hydrogen-fueled engines (developed in the Juno V program), with four of them in the third stage and one in the fourth stage. The amount of propellants needed for such a high-powered vehicle meant unusually large propellant tanks and a rocket that towered to a height of 79 meters. NASA, however, would also have a vehicle capable of fulfilling the dream of a manned lunar landing. "Despite its immense size," the Rosen report argued, "Nova is the first vehicle of the series that could attempt the mission of transporting a man to the surface of the moon and returning him safely to the earth."²²

During the course of the year, NASA's attention was directed primarily toward Juno V and Nova, although some name changes occurred. In February, the Department of Defense announced that the Juno V development program would henceforth be known as Project Saturn, with work to be continued at Huntsville under the direction of ABMA. The change in big booster nomenclature was consistent with von Braun's earlier inclination to refer to the clustered rocket as Saturn and logically followed the Jupiter vehicle in terms of christening boosters after successive planets in the solar system. The Saturn also reflected a proclivity within ABMA to name some boosters after ancient gods,²³ such as Juno and Jupiter.

Meanwhile, the von Braun team at Redstone Arsenal was becoming thoroughly enmeshed with the problem of selecting Saturn's upper stages. A "Saturn System Study," completed and submitted to ARPA on 13 March, contemplated the use of either Atlas or Titan upper stages. But dozens of potential upper-stage configurations were possible. This



The heart of the "von Braun team" that led the Army's space efforts at ABMA before transfer to NASA: left to right: Dr. Ernst Stuhlinger, Director, Research Projects Office; Dr. Helmut Hoelzer, Director, Computation Laboratory; Karl L. Heimburg, Director, Test Laboratory; Dr. Ernst D. Geissler, Director, Aeroballistics Laboratory; Erich W. Neubert, Director, Systems Analysis and Reliability Laboratory; Dr. Walter Haeussermann, Director, Guidance and Control Laboratory; Dr. Wernher von Braun, Director, Development Operations Division; William A. Mrazek, Director, Structures and Mechanics Laboratory; Hans Hueter, Director, System Support Equipment Laboratory; Dr. Eberhard F. M. Rees, Deputy Director, Development Operations Division; Dr. Kurt Debus, Director, Missile Firing Laboratory; and H. H. Maus, Director Fabrication and Assembly Engineering Laboratory.

made NASA a bit anxious because realistic planning was difficult as long as no firm booster configuration was drawn up. T. Keith Glennan expressed his concern in a memo to Roy Johnson at ARPA within a week of the publication of the "Saturn System Study." An early decision on Saturn upper stages was needed, he said, and he urged Johnson toward an early resolution of the issue.²⁴

ARPA's own plans for the Saturn booster remained tied to a combination with Centaur, to place "very heavy satellites in high orbits, especially for communications purposes." In testimony before Congress in late March, Johnson described the ARPA program for such satellites in equatorial orbits for global communications. More than that, he emphasized development of the Saturn cluster as a number one priority because it would serve a number of vehicle requirements for the next two years, not only for communications but also as an all-purpose space "truck" for a variety of missions, including launches of manned orbital satellites.²⁵

THE ABMA TRANSFER

The all-purpose Saturn suddenly ran into stiff opposition within the Department of Defense. Herbert York, Director of Department of Defense Research and Engineering, announced that he had decided to

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

terminate the Saturn program. In a memorandum to Johnson dated 9 June 1959, York rebuffed an ARPA request for additional funds. "In the Saturn case," York said, "I consider that there are other more urgent cases requiring support from the limited amount . . . which remains uncommitted." York's reasoning apparently stemmed from a position taken by other Eisenhower Administration advisors that the requirements of the Department of Defense for launching military communications satellites would be achieved more effectively by relying on existing ICBM boosters. Saturn had always been touted as the military's booster for such missions, so it did not seem to be needed any more. Saturn was a "costly operation being conducted at ABMA," York wrote, and advised Johnson, "I have decided to cancel the Saturn program on the grounds there is no military justification."²⁶ York's bombshell came as a real blow to ABMA, especially since the first H-1 engines for the Saturn cluster had begun arriving in Huntsville some weeks before, in April.²⁷

With NASA programs tied closely to the Saturn, as indicated in the earlier Rosen report, the launch vehicle staff in Washington immediately got to work to head off the York cancellation order as soon as they heard the news. Collaborating with Saturn supporters from within the Department of Defense, Rosen and Richard Canright from ARPA drafted a crucial memorandum in defense of the clustered booster program. They realized that Saturn as an Army project was in trouble apparently because the Army had no specific use for it. At that time, neither did NASA, although Rosen and Canright felt that the range of potential missions cited in the prior Rosen report offered, in the long run, enough justification to keep Saturn alive. Rosen and others in NASA were completely captivated by Saturn's promise. "We all had gut feelings that we had to have a good rocket," he said, emphasizing the appeal of Saturn's size. Rosen felt that he had "lived all his life with too small a launch vehicle."²⁸

Thus, in a tense three-day meeting, 16–18 September 1959, York and Dryden co-chaired a special committee to review Saturn's future and discuss the roles of the Titan C boosters and the Nova. Committee members included representatives from the Army, Air Force, and NASA as well as Canright from ARPA. After hours of intensive presentations and discussion, the Saturn backers finally carried the debate, but not without some conditions. Under York's prodding, it was agreed to start discussions to transfer ABMA and the Saturn project to NASA. York also insisted that such a transfer could be accomplished only with the Administration's guarantee for supplemental funding in support of Saturn.²⁹

Years later, reviewing the issue of Saturn's cancellation, York elaborated on his reasoning. For one thing, there seemed to be a strong feeling within the Department of Defense that Saturn tended to siphon off money, not only from important military projects in ABMA but from

STAGES TO SATURN

the Air Force as well. The Secretary of Defense twice turned down requests for a DX (priority) rating for Saturn, once in December 1958 and again in May 1959. Moreover, York felt that Saturn was simply too big for any military mission, and that included men in space. Big boosters of the Saturn class should be NASA's responsibility, he reasoned, because there was no urgent military application and because of York's own reading of the Space Act of 1958 and his understanding of Eisenhower's views on the matter. In the meantime, York apparently agreed to continue adequate funding of Saturn through ARPA until the issue of ABMA's transfer to NASA was resolved. As for the von Braun team at Huntsville, York recalled that von Braun himself "made it very clear in a face-to-face discussion in the Pentagon that he would go along only if I allowed Saturn to continue."³⁰

The near loss of the Saturn booster was a sobering experience. This close brush with disaster underscored NASA's problems in securing boosters developed and produced by other agencies; many in NASA now believed they had to have control of their own launch vehicles. In fact, York had already favored the transfer of ABMA, with responsibility for Saturn, to NASA. Late in 1958, when Glennan and Deputy Secretary of Defense Donald A. Quarles had proposed such a transfer, the Army and ARPA had strongly opposed the move.³¹ The ABMA transfer continued to beguile top NASA executives, and Hjornevik emphatically urged action on the matter. In a memo to Glennan late in January 1959, Hjornevik argued that the role of ABMA as consultant and supplier was operable as long as NASA was content merely to buy Redstone rockets in the Mercury program, but the rapid changes in an ambitious NASA launch program revealed a gap in the agency's capabilities, and Hjornevik left no doubt that NASA needed ABMA's competence. Hjornevik phrased his recommendations in no uncertain terms. "I for one believe we should move in on ABMA in the strongest possible way," he declared. "It is becoming increasingly clear that we will soon desperately need this or an equivalent competence." Hjornevik cited NASA's needs in managing the national booster program, especially the engines and "the big cluster," and the suggested joint funding as a means to "achieve a beachhead on the big cluster."³²

Roy Johnson, speaking for ARPA, emphasized the need for keeping the von Braun team together, particularly if a transfer occurred. "At Huntsville we have one of the most capable groups of space technicians in the country," Johnson said during congressional testimony in March 1959. "I think that it is a unique group . . . a national resource of tremendous importance." Then he added, "ABMA team is the kind of group that, if somebody had planned 10 years ago to create it, could not have been done better." Although Johnson told the congressional committee that he could work with ABMA in or out of the Department of Defense, he personally preferred it in the Department of Defense.

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

Among other things, he commented, he was not optimistic about lunar payloads taking precedence over the Saturn's role as a booster for military satellites.³³

NASA's lively interest in Saturn and the Huntsville group continued to mount. In mid-April, Glennan called a meeting of Dryden, Hyatt, Hjornevik, and others, including Abe Silverstein, Director of Space Flight Development. The NASA executives got together one Friday to assess the events of the past week and, among other things, to consider the question of Saturn. In the course of the discussion, the participants reached a consensus that the highly competent ABMA group had the best qualifications to develop the total Saturn vehicle, and they should be encouraged to forge ahead. At the same time, NASA should keep a sharp eye on its own interests in regard to Saturn and build a "significant financial and management role." A distinct takeover move, previously pushed by Hjornevik, did not take place for several months, simply because, as Glennan himself observed, NASA lacked a specific mission for Saturn that would justify wrenching the booster away from ARPA.³⁴

But the days of Saturn's ties to ARPA were numbered. After letting the issue simmer on a back burner most of the year, York raised the transfer issue again in the autumn of 1959, and this time got the support of both the Secretary of Defense and President Eisenhower.³⁵ Given the inclinations of the NASA hierarchy, ABMA's transfer from ARPA became inevitable. NASA's own requirements for a booster the size of the Saturn had been made more explicit as a result of the Research Steering Committee on Manned Space Flight, chaired by Harry J. Goett of NASA's Ames Research Center. The Goett committee, formed in the spring, had considered NASA goals beyond the Mercury program, and during the summer a circumlunar mission emerged as the principal item in NASA's long-range planning. A manned lunar landing required a much larger booster—Saturn. With potential mission and booster requirements finally outlined, satisfying Glennan's criteria to have a specific mission for the launch vehicle, total NASA responsibility for Saturn was obviously needed.³⁶

The transfer of ABMA, Saturn, and the von Braun team was phased over a period of nearly six months. NASA's technical direction of Saturn dated from a memorandum signed by Glennan on 21 October 1959 and by the acting Secretary of Defense, Thomas Gates, on 30 October, and approved by Eisenhower on 2 November. The document affirmed continuing joint efforts of NASA and the Department of Defense in the development and utilization of ICBM and IRBM missiles as space vehicles. Pointing out that there was "no clear military requirement for super boosters," the memorandum stated that "there is a definite need for super boosters for civilian space exploration purposes, both manned and unmanned. Accordingly, it is agreed that the responsibility for the super booster program should be vested in NASA."

STAGES TO SATURN

Specifically, the core of ABMA's Development Operations Division would be shifted to NASA—Saturn personnel, facilities, equipment, and funds. Both sides agreed on the unique talent of the von Braun team and the need to keep it intact. "The Department of Defense, the Department of the Army, and NASA, recognizing the value of the nation's space program of maintaining at a high level the present competence of ABMA, will cooperate to preserve the continuity of the technical and administrative leadership of the group."³⁷

The process of coordinating the administrative, technical, and physical transfer of the Saturn program progressed during the early months of 1960. To help provide guidelines and avoid as much chaos as possible, NASA called on McKinsey and Company, a private management consulting firm with offices in several major U.S. cities, including Washington. McKinsey and Company had helped NASA set up its own organization in 1958 and was thereby familiar with the agency's headquarters structure and personnel. By March 1960, the move was complete. On the 16th of the month, NASA assumed both administrative and technical direction of the Saturn program. The Goett committee, having wound up its work in December 1959, had pointed NASA in the direction of lunar-oriented missions as a goal. The transfer of the von Braun team, completed in the spring of 1960, gave NASA the expertise and a vehicle program to perform the task.³⁸

In the process of shedding ABMA's initials, the von Braun team now acquired a new set. By a presidential executive order on 15 March 1960, the space complex within the boundaries of Redstone Arsenal became the George C. Marshall Space Flight Center (MSFC). On 1 July 1960, Major General August Schomburg, commander of the Army Ordnance Missile Command, formally transferred missions, personnel, and facilities to von Braun, as Director of MSFC. Official dedication took place on 8 September with Mrs. George C. Marshall and President Dwight D. Eisenhower heading the list of distinguished visitors. In his public remarks, President Eisenhower noted Marshall's military career, his distinguished service as the Secretary of State, and the award to Marshall of the Nobel Peace Prize, the only professional soldier to have received it. "He was a man of war, yet a builder of peace," proclaimed Eisenhower. These sentiments fittingly paralleled the evolution of MSFC, with its origins in the Army Ballistic Missile Agency. In a brief, but moving ceremony, Mrs. Marshall unveiled a red granite bust of her late husband. Then von Braun escorted Eisenhower on a tour of the site, including a close-up inspection of the Saturn booster under construction.³⁹

UPPER STAGE STUDIES

During the months in which their relocation was being debated, ABMA personnel in Huntsville were still absorbed in the exercise of

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

trying to determine the configuration of upper stages for their multiengine booster. Design drawings of Saturn B and Saturn C studies during the first few months of 1959 showed clustered tank-and-engine first stages of 6.5 meters diameter and various combinations of upper stages of 6.5-meter and 3-meter diameters towering as high as 76 meters. The use of new hardware was apparently not contemplated; given ARPA's guidelines for economy in the program, a more realistic possibility was to add upper stages that used Titan or Atlas ICBM vehicles fitted directly to the clustered tankage and engines. By the spring of 1959, both ABMA and ARPA agreed on the feasibility of Titan and Atlas versions. ARPA advisors leaned more toward a decidedly hybrid concept in which a modified Titan second stage was used in combination with a modified Centaur third stage from the Atlas vehicle. Yet another twist in the evolution of Saturn upper stages came in July, when DOD's Director of Research and Engineering issued a new directive to both the Air Force and ARPA to consider the joint development of a second-stage vehicle keyed to the Air Force Dyna-Soar project, since the Saturn second stage and the Dyna-Soar booster appeared to be similar in design and concept. So ARPA ordered work on the Titan upper-stage studies to stop, pending further studies on this new DOD directive, although R&D work on the first-stage cluster forged ahead through the summer.⁴⁰

The decision to halt work in mating existing military missiles to the Saturn came as something of a relief to ABMA. Using such off-the-shelf hardware definitely narrowed the flexibility of mission planning. As a second-stage booster, it turned out that Jupiter just did not have the muscle, and the Atlas and Titan, although adequate in thrust for their ground-launch ICBM role, lacked performance capabilities as upper-stage vehicles to be ignited at altitude. Moreover, their 3-meter diameters limited their growth potential in relation to the possibilities of the far bigger Saturn. "In comparison," Willy Mrazek said, "this was like

Dedication of the George C. Marshall Space Flight Center. In the foreground with the bust of General Marshall are NASA Administrator Glennan, President Eisenhower, and Mrs. Marshall.



STAGES TO SATURN

considering the purchase of a 5-ton truck for hauling a heavy load and finally deciding to merely load a wheelbarrow full of dirt.”⁴¹ As a result of new evaluation studies that followed cancellation of work on the Titan as an upper stage, ARPA decided to forego requirements to employ existing hardware, and ABMA confidently embarked on a new series of design concepts for Saturn upper stages, utilizing large diameters that offered increased mission flexibility and payload capability. Undertaken in the fall of 1959, these new “Saturn System Studies,” as they were called, were conducted with an eye to NASA requirements in particular.⁴²

The last months of 1959 could be called a watershed period for NASA in many respects. The agency had acquired the von Braun team and sharpened the focus on upper stages for a multistage vehicle. In December, a critical judgment on the application of high-energy propellants for Saturn’s upper stages was in debate. The issue of high-energy propellants centered on liquid hydrogen in combination with liquid oxygen—and the use of liquid hydrogen (LH_2) did not have the whole-hearted support of von Braun or his staff at Huntsville.

At NASA Headquarters, on the other hand, Abe Silverstein and several others were convinced that LH_2 was the key to future Saturn success. Silverstein had joined NACA in 1929, and worked in wind tunnels at the Langley Laboratory. When the Lewis Propulsion Laboratory was formed in Cleveland, Ohio, in 1943, Silverstein joined the new organization and became its Associate Director in 1952. He had come to Washington in 1958 to become Director of Space Flight Development. For the next three years, Silverstein played an important role in policy decisions at NASA Headquarters before returning to Cleveland as Director of Lewis Research Center.

NASA had inherited an LH_2 development program as a result of NACA work carried on at Lewis Research Center throughout the 1950s; the work culminated in the successful test of a 89 000-newton (20 000-pound) thrust LH_2 engine and propellant injector in the late 1950s. The Lewis LH_2 group, led by Abe Silverstein, had been convinced of the practicality of LH_2 by subsequent successful test runs. The research at Lewis—and its successful prototype engine design—encouraged Silverstein to push hard for LH_2 engines in Saturn’s upper stages.⁴³ The first practical application of the LH_2 engine was planned as a high-energy stage, named Centaur, for Atlas or Titan. The plan stemmed from an ARPA directive to the U.S. Air Force’s Air Research and Development Command. During congressional testimony in March 1959, Roy Johnson noted early plans to incorporate an LH_2 -fueled stage (apparently the Centaur, or a close derivative) on the Saturn vehicle. Continuing research was solving problems of pumping LH_2 in large quantities, he explained, and he expected a breakthrough in propulsion for use in a second or third stage. Johnson’s enthusiasm for an LH_2 vehicle was unbounded. “It is a miracle stage as I see it,” he declared.⁴⁴ By the summer of 1959, the LH_2 rocket

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

also had support at NASA Headquarters, where Hyatt was corresponding with Silverstein about it.⁴⁵

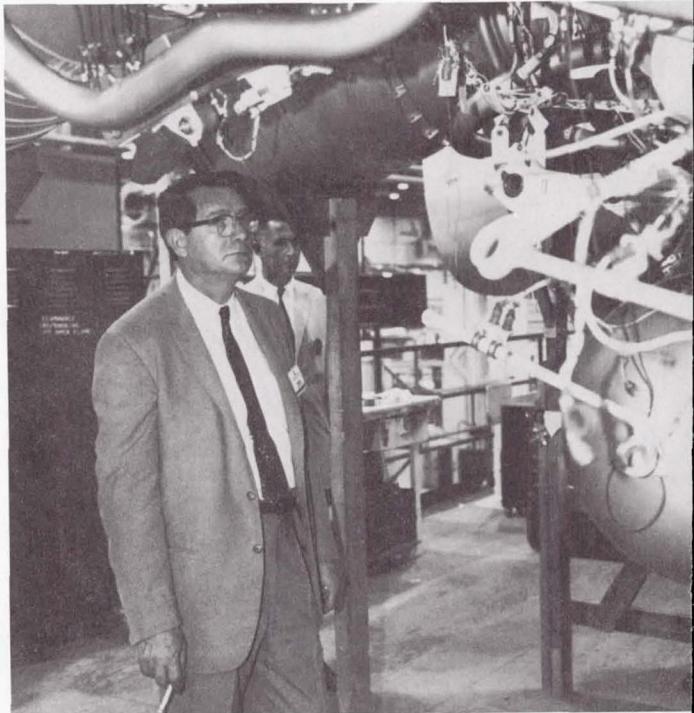
THE SILVERSTEIN COMMITTEE

Just before the Christmas holidays, the stage was set for a high-level conference at Headquarters to determine the basic configuration of the multistage Saturn. On 17 November, Associate Administrator Richard Horner told the Director of Space Flight Development to organize a study group to make additional recommendations concerning the transfer of the von Braun team to NASA, "to prepare recommendations for guidance of the development of Saturn, and specifically, for selection of upper-stage configurations." A "Saturn Vehicle Team" was organized; it comprised representatives from NASA, the Air Force, ARPA, ABMA, and the Office of the Department of Defense Research and Engineering (ODDR&E). Chaired by Abe Silverstein, the seven-man group was known as the "Silverstein Committee." In addition to Silverstein, the NASA representatives included Hyatt and Eldon Hall, and the other members were Colonel N. Appold (USAF), T. C. Muse (ODDR&E), G. P. Sutton (ARPA), and Wernher von Braun (ABMA).⁴⁶

When the Silverstein committee convened in December, not everyone was in favor of the untried LH₂ technology because LH₂ was widely thought to be too volatile and tricky to handle. Von Braun in particular expressed doubts about LH₂ even though the Saturn-Atlas combination had the Centaur's LH₂ system in the Atlas final stage, and he was definitely opposed to a new LH₂ Saturn second stage. On the other hand, several influential committee members made a forceful case for LH₂. Hyatt was already for it; Eldon Hall, not long before the committee had been organized, had analyzed the performance of launch vehicles using various combinations of propellants. Using his background in the work previously done at Lewis, Silverstein argued with all the persuasive powers at his command. It was just not logical, Silverstein emphasized, to develop a series of vehicles over a 10-year period and rely on the limited payload capability of conventionally fueled boosters with liquid oxygen and kerosene-based propellants. He was convinced that the use of LH₂ in the upper Saturn stages was inherently sound, and his conviction was the major factor in swaying the whole committee, von Braun included, to accept LH₂ boosters in the Saturn program. "Abe was on solid ground," von Braun acknowledged later, "when he succeeded in persuading his committee to swallow its scruples about the risks of the new fuel."⁴⁷

Next, von Braun had to convince his colleagues back at Huntsville. Before the committee adjourned, von Braun telephoned the Redstone Arsenal to talk to Mrazek, one of the key team members who had come with him from Germany, and the two men brainstormed the possibilities.

Abe Silverstein, NASA's Director of Space Flight Development, is shown touring a rocket engine facility.



As Mrazek recalled his phone conversation, von Braun made the following points: The Saturn could not use existing hardware for the upper stages—it needed an original design; the Saturn plan should stress the new hydrogen technology and the Centaur's engines; and the hydrogen upper stage would need six engines. This final aspect could have been controversial because some experts still harbored strong doubts about the use of eight conventional, though proven, rocket engines for the first-stage booster. There would be even more carping about a half dozen new and untried engines burning exotic liquid hydrogen. But von Braun said he was not overly concerned about the cluster of six hydrogen engines, since at least a dozen Centaur launches were scheduled before the first Saturn would have to go up. The ABMA group could profit from whatever trials and tribulations the Centaur engines developed, with plenty of time to iron out any problems before the first Saturn left the launch pad. In short, von Braun was confident of success with the new hydrogen technology, and Mrazek agreed; so the scenario was finally set.⁴⁸ (See chapter 5 for further details of LH₂ technology.)

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

In the spring of 1960, as the word of NASA's decision to rely on the novel propellant combination for Saturn reached the public, Eldon Hall and Francis Schwenk, from the Office of Launch Vehicle Programs at NASA Headquarters, outlined the reasons for the choice. The higher vehicle performance required for advanced missions simply required higher energy propellants, they explained. The staging of several rockets using conventional propellants rapidly reached optimum design limits, because advanced missions and payloads required more thrust and more engines—which meant heavier rockets with bigger tanks and engines and proportionately less efficiency in design and capability. On the other hand, high-energy propellants promised the best results for advanced missions requiring high escape velocities. "The choice of high-energy upper stages for Saturn is based almost entirely on the fact that, with present knowledge of stage construction, at least one of the upper stages must use high-energy propellants if certain desirable missions are to be accomplished with this vehicle," Hall and Schwenk emphasized. So "the Saturn program was established for early incorporation of a high-energy second stage into the vehicle system."⁴⁹

In the course of the deliberations of the Silverstein committee, three types of missions for the Saturn vehicle emerged. First priority was given to lunar and deep-space missions with an escape payload of about 4500 kilograms. Next in order of priority came satellite payloads of about 2250 kilograms in a 24-hour equatorial orbit. Finally, the committee considered the possibility of manned missions involving the Dyna-Soar program, in which a two-stage vehicle would be used to put 4500 kilograms into low orbit. On the basis of these assumptions, the committee stressed the evolutionary pattern of Saturn development and its potential for a variety of future roles. "Early capability with an advanced vehicle and possibilities for future growth were accepted as elements of greatest importance in the Saturn vehicle development."

Once more, the Saturn Vehicle Team reviewed the wide array of potential configurations, reduced the number of choices to six, and began to weed out the least promising. The A-1 version, with modified Titan and Centaur upper stages, would provide the earliest flight schedules and lowest costs with existing hardware. It was rejected because it could not meet lunar and satellite payload requirements and because the slender 3-meter-diameter upper stages were considered to have potential structural weaknesses. The A-2 type, with a cluster of Intermediate Range Ballistic Missiles (IRBMs) in the second stage, also saved money and promised early availability but did not have the capability for some of the planned missions. A proposed B-1 vehicle met all mission requirements but needed a totally new stage with conventional fuels. The B-1 type was expensive, would take a lot of time to develop, and had some shortcomings for advanced missions.

STAGES TO SATURN

Moreover, all first three candidates needed high-energy propellants in the top stage. So why restrict the promise of LH₂ to the top stage alone? "If these propellants are to be accepted for the difficult top-stage applications," the committee concluded, "there seem to be no valid engineering reasons for not accepting the use of high-energy propellants for the less difficult application to intermediate stages." The Saturn family of rockets finally envisioned by the Silverstein committee included C-1, C-2, and C-3, all with LH₂ in the upper stages. The three-stage C-1 met the mission requirements and used Centaur engines in the LH₂ upper stages. The second stage had four uprated Centaur engines, designated the S-IV stage, and the S-V top stage was the Centaur itself, with two engines. The hop-scotch numbering occurred because of the "building block" concept, in which hardware was used as available, the concept was tested, and then newer and advanced stages were incorporated in the next major configuration. During C-1 development and flight, for example, a new S-III stage for Saturn C-2 would be prepared with the use of a newer, more powerful generation of LH₂ engines. As the development and flight test of Saturn C-2 proceeded, the S-II stage would be worked up with four of the newer LH₂ engines. The final C-3 vehicle would stack all the various stages together as a five-stage booster. Further, the Saturn Vehicle Team suggested that the first stage of the C-3 model might even include an F-1 engine to replace four of the cluster of eight uprated H-1 engines.

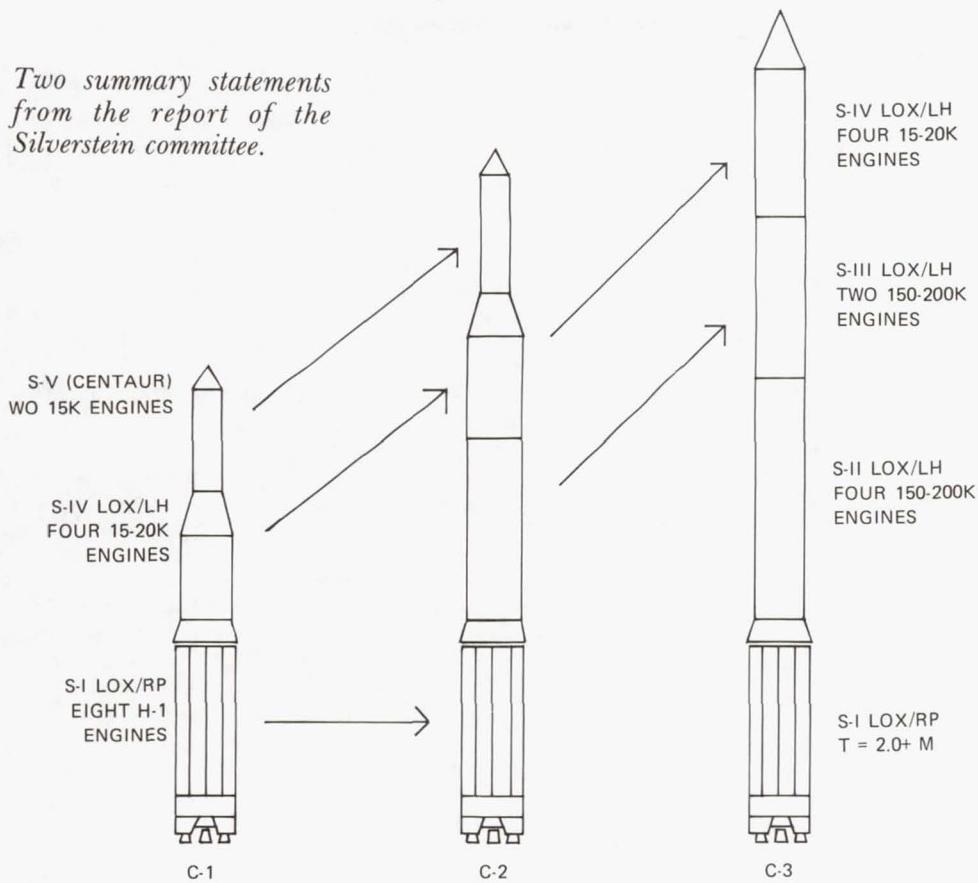
In its final recommendations for the phased development of Saturn C-1 through C-3, the Silverstein committee emphasized the building block concept keyed to the Saturn first-stage cluster, along with hydrogen-oxygen propellants in all the upper stages. Proceeding from the Centaur technology under development at the time, the committee urged immediate development of a new LH₂ engine and initiation of design studies for the S-II and S-III stages to use the more powerful engines.⁵⁰

PRIORITIES AND GOALS

With in-house capability established, in the form of the ABMA transfer, and with immediate vehicle guidelines established as a result of the Silverstein committee, NASA now proceeded to refine its priorities and goals.

The ultimate goal was a lunar landing. The Director of Lunar Vehicles, Donald R. Ostrander, stated in a planning conference for NASA and industry in January 1960: "The principal mission which we have used as an objective in these planning studies has been that of a manned landing on the moon and return to earth."⁵¹ Looking ahead, NASA executives told Congress during hearings late in the same month that the agency planned a circumlunar flight by 1970 and a manned

*Two summary statements
from the report of the
Silverstein committee.*



STAGE	1	2	3	4
A-1	LOX/RP EIGHT H-1 ENGINE CLUSTER	LOX/RP TITAN 120" DIA.	CENTAUR 120" DIA. TWO 15K ENGINES	
A-2		CLUSTER OF IRBM'S	CENTAUR 120" DIA. TWO 15K ENGINES	
B-1		LOX/RP 220" DIA.* FOUR H-1 TYPE ENGINES	LOX/LH 220" DIA.* FOUR 15-20K ENGINES	CENTAUR 120" DIA. TWO 15K ENGINES
C-1		LOX/LH 220" DIA.* FOUR 15-20K ENGINES	CENTAUR 120" DIA. TWO - 15K ENGINES	
C-2		LOX/LH 220" DIA.* TWO 150-200K ENGINES	LOX/LH 220" DIA.* FOUR 15-20K ENGINES	CENTAUR 120" DIA. TWO 15K ENGINES
C-3	LOX/RP 2.0+ MILLION POUND THRUST ENGINE CLUSTER	LOX/LH 220" DIA.* FOUR 150-200K ENGINES	LOX/LH 220" DIA.* TWO 150-200K ENGINES	LOX/LH 220" DIA.* FOUR 15-20K ENGINES

*Nominal tank diameter

H-1 Engine - 165,000 to 188,000 lb. thrust

STAGES TO SATURN

lunar landing soon after. The agency also estimated the cost at \$13 to \$15 billion over the coming decade, and Associate Administrator Horner explained the need to look so far ahead and plan a budget:

Virtually all of our key programs presume a scheduled progress in launch vehicle and spacecraft development. These major developmental tasks frequently require time periods of 5 to 6 years for completion and can be substantially longer under given circumstances of technological progress and research availability.

Thus, although the usefulness of highly tentative plans might be questioned, long-term objectives, on the order of 10 years in advance of today's program, are essential to keep our development activities properly focused.

The actions we initiate this year and next in the vehicle development program will have a determining influence on our capabilities for meeting national objectives in the last half of this decade and even beyond. Accordingly, we have developed a 10-year plan, one which we expect to modify from year to year on the basis of realized experience, development progress, and resource availability. It is formulated around the requirement that its implementation must so utilize the resources of the United States that our national role as a leader in the aeronautical and space sciences and their technologies is preserved and steadily enhanced. We have also assumed that a steady growth in the scale and intensity of our efforts, especially for the next 5 years, is an essential basis for consistent and fruitful efforts in meeting this requirement.⁵²

As NASA prepared to forge ahead on its 10-year program in 1960, the agency enjoyed increased support from Eisenhower, and Glennan won an important advantage for the Saturn program in terms of a high priority endorsement. "As we have agreed," the President wrote to Glennan on 14 January, "it is essential to push forward vigorously to increase our capability in high thrust space vehicles." In the same directive to Glennan, Eisenhower gave his authorization to prepare an additional funding request for the balance of fiscal 1960 and 1961, "to accelerate the super booster program," and to use overtime as needed, "consistent with my decision to assign a high priority to the Saturn development." Four days later, on 18 January, the rating for highest national priority (DX rating) became official, authorizing the use of overtime wages and giving Saturn precedence for materials and other program requirements.⁵³

The configurations of the Saturn family were still in a state of flux, however, and the Nova was still a probability in the NASA scheme. Straightening out the lines of development and mission application became an issue that absorbed personnel in program studies and committee meetings for another two and a half years. Although the Saturn Vehicle Team did not mention Nova in their recommendations, the towering booster figured prominently in plans for manned lunar landings. During a meeting on advanced propulsion requirements at NASA Headquarters in early June 1960, the Huntsville group discussed Nova "for manned lunar landing and return," in a configuration that

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

would boost a 81 600-kilogram payload to escape velocity and return 6800 kilograms to Earth. The vehicle featured eight of the 6 700 000-newton (1.5-million-pound) thrust engines in the first stage, four LH₂ engines in the second stage, and one LH₂ engine each in the third and fourth stages. Data for a C-2 launch with assisted boost from Minuteman missile solid-fuel strap-ons were also discussed, although "Marshall people were not enamored with the idea of any changes to the C-2."⁵⁴ Therefore, the Saturn configurations remained keyed to liquid propulsion engines, especially the LH₂ propulsion systems. NASA planners considered using the Saturn "C" series of vehicles for manned space stations, manned circumlunar missions, and unmanned lunar and planetary probes. Manned lunar excursions, Homer Stewart reminded NASA Administrator Glennan, would definitely require the application of the 6 700 000-newton (1.5-million-pound) thrust engine (known as the F-1) used in a cluster, probably in a Nova vehicle, and if the LH₂ program developed any snags, he warned, the Saturn program would quickly find itself in dire trouble.⁵⁵

Toward the end of 1960, NASA planners decided it was time to review the space program once again and make more specific recommendations for future development in the Saturn and Nova projects. Early in November, NASA laid out its milestone for the next 10 years. "A ten-year interval has no special significance," the report asserted, "yet it is considered to be an appropriate interval since past experience has shown that the time required to translate research knowledge into operationally effective systems in similar new fields of technology is generally of this order." This time span permitted opportunity to establish mission goals and plans and coordinate the development of spacecraft and appropriate booster hardware. Apparently there was already some confusion about terminology, since the "Proposed Long Range Plan," as drafted by the Headquarters Office of Program Planning & Evaluation, included some definitions. "Launching vehicle" meant a first-stage booster and upper stages to inject a spacecraft into proper trajectory. "Spacecraft" included the basic payload as well as guidance and its own propulsion systems for trajectory modifications following injection. The term "space vehicle" encompassed the entire system— launching vehicle plus spacecraft.⁵⁶

With definitions thus established, the document discussed the major launch vehicles, or boosters, under NASA cognizance: C-1, C-2, and Nova. The C-1 and C-2 descriptions closely followed the analysis prepared by the Silverstein committee the previous year, the descriptions reaffirming the building block concept with the C-1 as a three-stage vehicle and the C-2 as a four-stage booster including a newly developed second stage with a cluster of four 890 000-newton (200 000-pound) thrust hydrogen engines. The R&D for the Centaur and the new hydrogen engines appeared to be the biggest gamble in the long-range plan. The decision to use LOX-LH₂ engines in C-1 and C-2 upper stages "was based on a calculated risk," the report stated, that such engine technology

STAGES TO SATURN

would come along smoothly enough to keep the building block sequence on schedule. By FY 1964–1967, according to the "Proposed Long Range Plan," the C-1 should be operational in support of preliminary Apollo orbital missions, as well as planetary probes and as a test bed for advanced technology electron engines and nuclear engines. The C-2 should be ready somewhat later to place twice the payload into orbit, as well as for launching deep-space probes.⁵⁷

As for the Nova, "its primary mission is to accomplish manned lunar landings," the plan said. Nova was admittedly still in the conceptual stage, since its size and ultimate configuration depended on space environmental research, progress in advanced chemical engines such as the F-1, and potential development of nuclear engines. The Nova, with an F-1 cluster combination to total 53 million newtons (12 million pounds) of thrust in the first stage, seemed to be the most feasible, and the Nova booster could make a manned lunar landing mission by direct staging to the moon and return or by a series of launches to boost hardware into low orbit for a series of rendezvous operations, building up a space vehicle in low orbit for the final lunar mission.⁵⁸

As a prelude to the ambitious moon missions, a lot of basic research had to be integrated into the plans for the launch vehicle development. Guidance and control was one area singled out for special attention, requiring advances in the state of the art in accelerometers; in cryogenic, electromagnetic, and electrostatic support systems for gyros and attitude control; inertia wheels; in long-life gyro spin axis bearings. The long-range plan noted research challenges in terms of heating and other aerodynamic problems, along with mechanical, hydraulic, electrical, electronic, and structural difficulties. The space environment created a wide range of potential trouble spots in metals, plastics, seals, and lubricants. The scaled-up size of Saturn and Nova suggested difficulties in devising adequate automatic test equipment and techniques for the fabrication and assembly of oversized components. The long-range plan provided the opportunity to look ahead and anticipate these problem areas, giving NASA designers and engineers the chance to start working on solutions to these and other problems that were sure to crop up in the course of launch vehicle development.

The long-range plan also projected a series of key dates in the development of launch vehicles:

1961	first suborbital astronaut flight
	first launch Saturn 1st stage
1963	launch 2-stage C-1
	launch 3-stage C-1
1964	qualification of 200K LH ₂ engine
1965	qualification of 1.5-million-pound engine

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

1966-1967	launch 3-stage C-2
1968-1970	Apollo manned orbiting lab and circumlunar flights
Beyond 1970	manned lunar landing

The long-range plan also estimated the costs.⁵⁹ NASA's plans at this time found support from the President's Scientific Advisory Committee, which had formed a special ad hoc group to examine the space program to date and analyze its goals, missions, and costs. In its report, released on 14 November, the group advanced the rationale that "at present the most impelling reason for our effort has been the international political situation which demands that we demonstrate our technological capabilities if we are to maintain our position of leadership." The report considered the scientific motive of much less significance than prestige but commented that "it may be argued that much of the motivation and drive for the scientific exploration of space is derived from the dream of man's getting into space himself."⁶⁰ The committee wondered if 25 test flights for the C-1 and 16 for the C-2 were enough to qualify the vehicles for manned launches but gave NASA good marks overall on their plans and schedules. Further, the committee endorsed the R&D plans for liquid hydrogen technology and encouraged development of larger post-Saturn launch vehicles like the Nova.⁶¹

But NASA was not entirely free from difficulties. NASA Administrator Glennan departed NASA at the end of the Eisenhower Administration and resumed his position as president of Case Institute. Several weeks passed before President John F. Kennedy's new Administration settled on a successor. Lyndon Johnson, the Vice-President, still played a strong hand in space program planning, and favored someone with strong administrative credentials. Other advisers contended that NASA needed a technical man at the helm. As the Kennedy Administration prepared to take over early in 1961, the space agency received some hard knocks from the President-elect's science advisor, Jerome B. Wiesner, of the Massachusetts Institute of Technology. Kennedy announced Wiesner's appointment on 11 January and released the "Wiesner Report" the next day.⁶² Officially titled "Report to the President-Elect of the Ad Hoc Committee on Space," the report gave due credit to the "dedication and talent" that had achieved notable advances in space exploration during the past few years but implied deficiencies in the booster program. "Our scientific accomplishments to date are impressive," the document observed, "but unfortunately, against the background of Soviet accomplishments with large boosters, they have not been impressive enough."

Among other recommendations, the Wiesner report urged technical competence in the positions of Administrator and Deputy Administrator, along with technical directors for propulsion and vehicles, scientific programs, nonmilitary space applications, and aeronautical programs.⁶³

For several weeks, contact with the new Kennedy Administration was

STAGES TO SATURN

haphazard. The Wiesner report aroused real concern among NASA personnel; there was a definite feeling that the report was neither fair nor carefully prepared. The issue of NASA leadership was resolved in February, when James E. Webb was nominated as Administrator. Vice-President Johnson had found the managerial talent he wanted. A lawyer and ex-officer in Marine Corps aviation, Webb had headed the Bureau of the Budget and served as Undersecretary of State during the Truman Administration. At the time of his appointment, Webb was actively involved in the management of large corporations and was an active member of several professional administrative and policy organizations. Webb was sworn in by 14 February, with Dryden again as Deputy Administrator. Members of the Wiesner committee were subsequently given a deeper insight into the NASA program and organization that produced a much more positive feeling on their part. The organizational structure of the space agency was indeed firmed up, and a healthy rapport was established with the new Administration.

During the 1960 campaign, Kennedy had made an issue of the Eisenhower record in space, although the question was addressed more in terms of the so-called "missile gap" than in terms of space exploration. After the election, however, the Kennedy Administration evinced a growing interest in NASA's programs. In February, Webb was asked to conduct a thorough review and make recommendations; although a revised NASA budget request was trimmed, the space agency went to Congress in March with a program that amounted to over \$125 million more than Eisenhower's original \$1.1 billion for fiscal 1962. On 10 April, Kennedy submitted a specific request to amend the Space Act, in keeping with a campaign statement, to revive the dormant National Aeronautics and Space Council, and to appoint Vice-President Lyndon Johnson, a partisan of space exploration, as its head. In sum, the national space program under the new Kennedy Administration began moving with positive, if modest, momentum. Rapid acceleration occurred as a reaction to dramatic Russian progress.⁶⁴

The successive achievements of Russian efforts in space exploration early in 1961 not only intensified NASA's plans in aeronautics, but also influenced President Kennedy's commitment to a more active program by the United States. The day after Webb and Dryden were sworn in, the Soviet Union launched a probe to Venus from a space vehicle in a parking orbit; Kennedy remarked at a public press conference that the Russian lead in space boosters was "a matter of great concern."⁶⁵ Then, on 12 April, while Congress was debating additional funds for NASA's budget in the coming year, a Russian booster put Yuri Gagarin into Earth orbit—the first human to orbit the Earth. On the evening of the following day, President Kennedy hosted a meeting at the White House, inviting Webb, Dryden, Wiesner, Theodore Sorensen, and several others, includ-

AEROSPACE ALPHABET: ABMA, ARPA, MSFC

ing a reporter, Hugh Sidey, from *Life* magazine. The conversations revealed Kennedy's considerable concern about the Soviet Union's growing preeminence in space. The President speculated about the steps the United States could take to improve its own activities and about the costs involved in an accelerated program. Dryden observed that it might cost up to \$40 billion to fund a program to land on the moon before the Russians, and even then, the Russians might make it before the Americans. But the President clearly wanted action. "There's nothing more important," he was remembered as saying.⁶⁶ Not long afterward, in remarks to the Congress, Kennedy firmly asserted that it was "time for this nation to take a clearly leading role in space achievement, which in many ways may hold the key to our future on Earth."⁶⁷ Shortly thereafter, Kennedy instructed Johnson and the Space Council to study space projects that would give the United States a visible lead in space exploration.

Congress also wanted more information from NASA about costs and the problems of landing on the moon ahead of the Russians. In mid-April, Webb repeated to Congress what Dryden had told the President. The cost would be anywhere from \$20 to \$40 billion. Some congressmen suggested the possibility that the Russians might attempt a lunar landing around 1967, in conjunction with the 50th anniversary of the Russian Revolution. With massive infusion of funds, the representatives asked, could the Americans beat a Russian landing? In his response, Associate Administrator Robert Seamans was wary. The target date of 1967 for the Russians was only an assumption, he said. Current NASA planning put an American lunar landing in 1969 or 1970 at the earliest. To reduce American intentions by three years was not necessarily an impossibility, Seamans stated, but would certainly be tremendously expensive in the short term.⁶⁸

During April and May, the executive and legislative branches of government blossomed committees and working groups like flowers in a spring garden. Within NASA, planning groups funneled a series of honed and polished study papers to the White House for Kennedy's consideration, and the Department of Defense and the space agency refined mutual goals and individual efforts to ensure cooperation where necessary and to avoid needless redundancy. The nexus of all these streams of activity culminated in President Kennedy's State of the Union message on 25 May 1961. The manned space program would be the province of NASA, a civilian agency, not a military agency. He proposed to increase NASA's 1962 budget by more than \$500 million. Kennedy left no doubt as to NASA's objective or its schedule for realization. "This nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon, and returning him safely to the Earth."⁶⁹

STAGES TO SATURN

SUMMARY

Haltingly, a national space program coalesced around a new entity, the National Aeronautics and Space Administration. After turning to the Department of Defense for its large boosters, funded through ARPA and under development by ABMA, NASA realized the need to control its own booster program when the Saturn project was nearly canceled owing to budgetary cross-currents. The eventual transfer of the von Braun team and the Saturn booster was a significant step forward for NASA. During 1959–1960, important agreements on upper stages and the use of high-energy LH₂ technology were also worked out, capped by President Kennedy's decision to achieve a manned lunar landing within the decade of the 1960s. The next moves required decisions on mission profiles and production facilities.

3

Missions, Modes, and Manufacturing

At the time of Kennedy's historic pronouncement, the booster vehicle program was still in flux. The Saturn rocket was considered a multi-purpose vehicle, and the Department of Defense was still planning Earth-orbital missions using Dyna-Soar. During the summer and fall of 1960, NASA and Air Force executives were still engaged in mission studies using Dyna-Soar as a payload for Saturn.¹ By January 1961, the Dyna-Soar appeared to have won an even stronger place in Saturn mission studies. In a planning session at Huntsville, the second stage of the Saturn C-2 configuration study was firmed up as to trajectory, performance, and structural considerations. All of these parameters derived from a Saturn and Dyna-Soar vehicle combination with the Dyna-Soar as the upper stage.² Yet the C-2 configuration itself was only a paper study, and Saturn configurations changed rapidly in the early months of 1961.

At the opening of the new year, as NASA was still formulating its mission plans and goals, Glennan injected a note of caution into discussions involving a manned lunar landing because a formal announcement from the White House had not yet been made. In general, the mood at NASA was to proceed toward the lunar goal along a broad base of action, leaving open a variety of options including Department of Defense missions like Dyna-Soar. If all the options were pursued, then a broad series of booster vehicles needed to be developed, and von Braun was already hoisting storm signals about the allocation of manpower in NASA programs. At current levels, he noted, NASA would most certainly find itself overextended by trying to maintain parallel development of both the C-2 and the Nova.³

STAGES TO SATURN

CONFIRMING THE CONFIGURATIONS

During 1961, configurations seemed to change month by month. In January, the C-1 vehicle changed from a three-stage to a two-stage booster, eliminating the S-V upper stage to leave only S-I and S-IV stages; but S-V development continued during February. By May, the C-1 had become a possible three-stage vehicle again, including Block I and Block II interim versions. In February, the C-2 was ticketed as a three-stage vehicle for Earth-escape missions (featuring an S-II second stage); in May, there was talk of a need for an even more powerful vehicle for circumlunar missions; in June the C-2 was dropped in favor of a C-3, although Nova would continue; later in the year, there were plans for a C-4, along with a solid-booster C-1. By the end of the year, there was also the C-5.⁴ One result of this was the decline of Dyna-Soar, whose position as a NASA payload essentially evaporated after the C-2 cancellation in June.⁵

The rise and fall of vehicle configurations reflected the rapidly shifting concepts of mission profiles, payloads, schedules, and money. The fluctuating pattern of Saturn configurations and numbers created confusion even among those in government who were close to the program, as Hugh Dryden admitted in a letter to Hugh Odishaw, of the National Academy of Sciences. Written in March 1961, the letter also revealed the concern of some observers that future development of Saturn was a "dead end road." Such talk irritated Dryden. If critics were referring to the Saturn S-1 first stage, with a total thrust of 1.5 million pounds, then he admitted that maximum development was self-evident, since the propulsion came from the most advanced engines available from the ballistic missile program. Dryden complained that critics did not allow for advanced Satellites of much improved performance, using what he called "the Saturn engine."⁶ He could have been referring to either the F-1 or the liquid hydrogen propulsion system (known as the J-2), but both types of engine would be crucial for advanced configurations involving more ambitious missions. The C-3 version, for example, boasted two F-1 engines in the first stage (double the thrust of the existing Saturn C-1 first stage), four J-2 engines in the second stage, and a pair of J-2s in the third stage. During a high-level NASA conference in late July 1961, Milton Rosen emphasized that the United States was still in contention in the race for a manned lunar landing "only because we initiated J-2 and F-1 development at a relatively early date." If the United States intended to maintain a competitive position, Rosen warned, NASA had to capitalize on the use of these propulsion systems, both of which were still under development.⁷

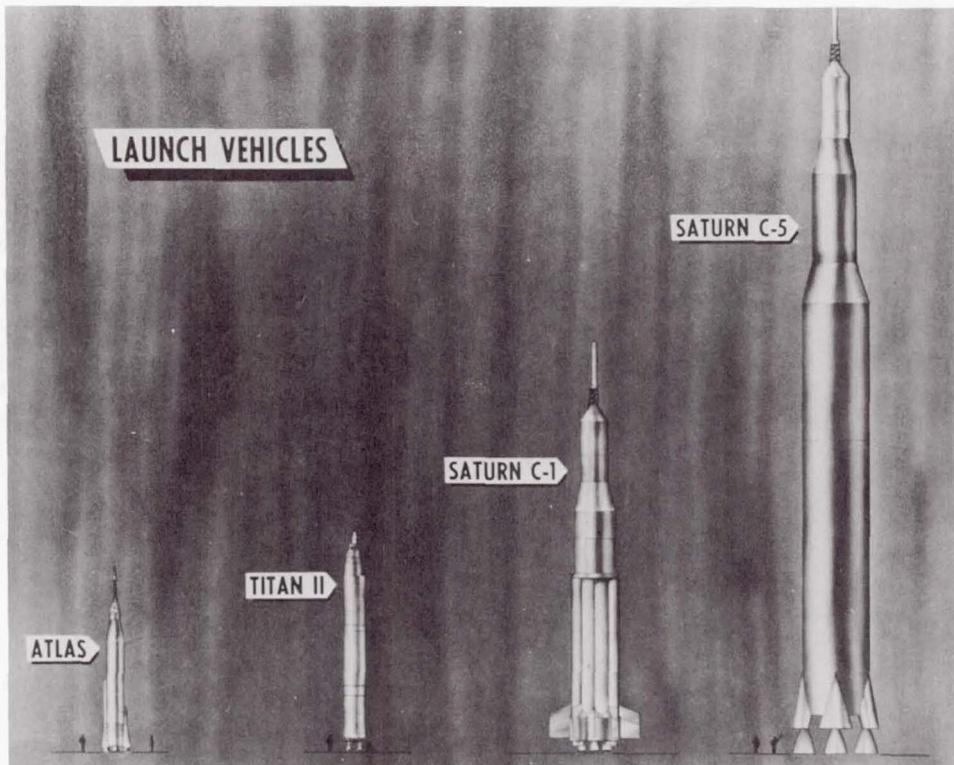
Certainly if the F-1 and J-2 were to be the optimum engines, then the vehicle known as the Saturn C-5 promised to be an optimum booster. The designers at MSFC made a firm commitment to the C-5 by late 1961,

MISSIONS, MODES, AND MANUFACTURING

and NASA Headquarters gave formal approval for development on 25 January 1962. The C-5 was a three-stage vehicle, with five F-1 engines in the first stage, five J-2 liquid-hydrogen engines in the second stage, and one J-2 in the third stage. The C-5 could handle a number of missions, including 113 000-kilogram payloads into low Earth orbit, or 41 000 kilograms on a lunar mission, which could be a circumlunar voyage or a manned landing.⁸

During a spring meeting of various NASA managers at Langley Research Center, Hampton, Virginia, Ernst Geissler of MSFC reviewed the status of the booster program. Despite the welter of configuration changes and confusing nomenclature, one of the guiding principles of the vehicle development program continued to be the building block concept, an idea even more significant with the passage of time and realization of the immense costs and complexities of the program. "By qualifying individual components, such as stages, a fewer number of flights are necessary for high reliability of the total vehicle system," he emphasized. Moreover, the step-by-step approach allowed the space agency to experiment with various maneuvers in orbit, as required for different mission concepts.⁹ The Saturn C-1, at that time, was planned for vehicle development launches that would also include testing of the planned lunar spacecraft module in orbit and reentry, culminating in a series of manned flights. The spacecraft would thus be qualified in plenty of time, ready for launch aboard the C-5. Qualifying some of the C-5 hardware suggested possible problems, however, unless some preliminary flight tests occurred. Geissler referred to still a different launch vehicle, the C-1B. This interim vehicle, using the C-5's intended third stage as its own second stage, would take advantage of the proven C-1 first-stage booster. Thus, the C-1B would be able to qualify certain hardware and systems for the C-5, while demonstrating the feasibility of orbital operations inherent in C-5 mission concepts.¹⁰

Geissler summarized three principal modes for a lunar landing mission with the C-5 vehicle. Lunar orbit rendezvous (LOR) involved descent to the lunar surface from lunar orbit by using a small spacecraft that separated from a parent lunar satellite and then rejoined the orbiting spacecraft for the return home. Earth orbit rendezvous (EOR) involved the landing of a larger vehicle directly on the lunar surface, thus eliminating the descent and ascent of a separate spacecraft from orbit. But the EOR mode required rendezvous techniques in building up the necessary vehicle in Earth orbit. Geissler explained two different approaches. After launching two vehicles, the upper stages of each could be connected to form the lunar vehicle. An alternative was to transfer oxidizer from one vehicle to the other in Earth orbit. There was one more feasible way of going to the moon: if a large enough vehicle could be built, a single launch would suffice. MSFC refused to give up on Nova. The Nova in the spring of 1962 was to have 8–10 F-1 engines in the first stage, and a



Early design concepts of C-1 and C-5 versions of the Saturn launch vehicles.

second stage mounting a powerful new LH₂ engine, the M-1, under development by Aerojet General. Although Geissler predicted a test launch of the Nova by the autumn of 1967, the logic of development favored the C-5 because it was predicted to be fully operational by November 1967.¹¹

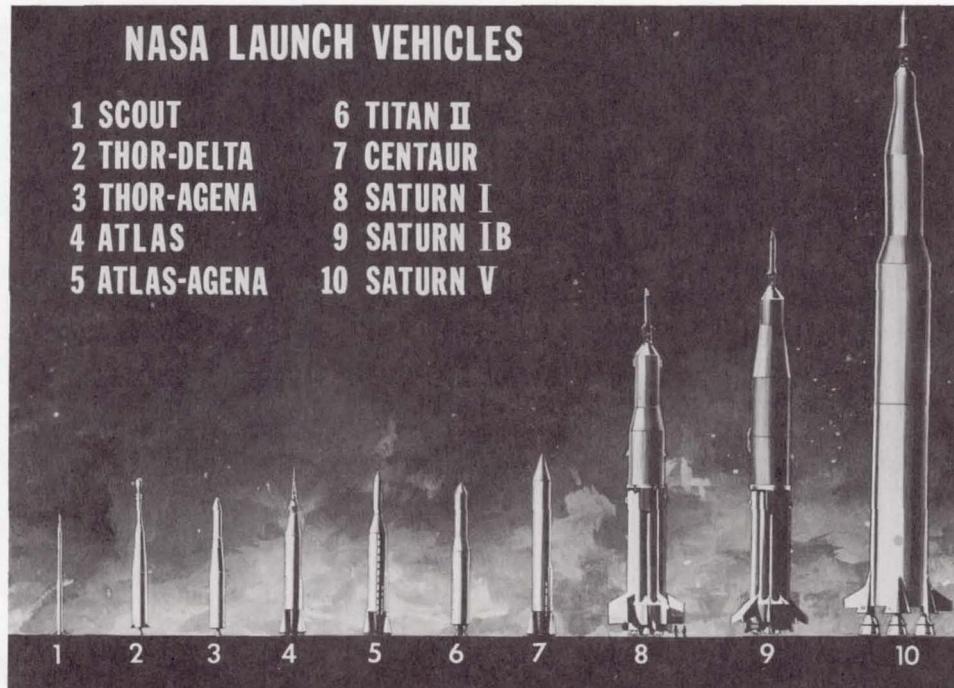
Nova, like Dyna-Soar, seemed to evaporate as other issues were settled that placed a premium on the development of its nearest competitor, the C-5. On 11 July 1962, NASA officially endorsed the C-1B as a two-stage Saturn for Earth-orbital tests of Apollo hardware. At the same time, NASA confirmed the choice of the LOR mode for the lunar mission, thereby focusing development on the C-5. Early in 1963, NASA Headquarters announced a new nomenclature for its large launch vehicles. The C-1 became Saturn I, C-1B became Saturn IB, and C-5 became Saturn V. Nova was not even mentioned.¹²

TO RENDEZVOUS OR NOT TO RENDEZVOUS

The disarmingly simple NASA statement of 11 July 1962, confirming the choice of LOR as the mode, represented only the tip of a bureaucratic iceberg. The choice of LOR came after a series of skirmishes and

NASA LAUNCH VEHICLES

- | | |
|---------------|-------------|
| 1 SCOUT | 6 TITAN II |
| 2 THOR-DELTA | 7 CENTAUR |
| 3 THOR-AGENA | 8 SATURN I |
| 4 ATLAS | 9 SATURN IB |
| 5 ATLAS-AGENA | 10 SATURN V |



The stable of NASA launch vehicles that were actually built and flown.

engagements among various NASA centers and within Headquarters. The struggle in reaching the final decision also suggested some of the problems to be faced by NASA management when one center had responsibility for the launch vehicle and another organization had the payload. The problems were compounded when both were trying to fashion programs and develop hardware without always knowing what each would require in the end.

The von Braun group, after all, had been developing both payload and boosters as integral systems for years. Now it would be necessary to defer to different design teams and accept outside judgments about payloads. In the case of Saturn, the payload development stemmed from the Space Task Group (STG) originally set up in October 1958 to manage Project Mercury. Located physically at Langley Research Center, Virginia, STG reported to the Goddard Space Flight Center at Greenbelt, Maryland. Beginning in 1959, STG received management responsibilities for studies leading to Project Apollo.¹³ In the spring of 1960, STG and MSFC began closer contact when STG organized a special liaison group, the "Advanced Vehicle Team," nine men headed by R.O. Piland and reporting directly to the STG chief, Robert R. Gilruth. Among other things, the Advanced Vehicle Team was to maintain appropriate contact with the various NASA centers, and, specifically, to maintain "the necessary liaison with the Marshall Space Flight Center in matters

STAGES TO SATURN

pertaining to the development and planned use of boosters in the advanced manned space flight program."¹⁴

Early on, participants in the liaison effort discovered that their style did not always mesh with that of MSFC. One trip report from an STG team member in October 1960 noted von Braun's desire for additional meetings in November and December, and added, somewhat peevishly, "Dr. von Braun wants to participate. This probably means another ballroom meeting." Apparently the MSFC method was to have a large gathering for a semiformal presentation, then break into smaller groups for detailed discussions. "I've reached the opinion that MSFC staff have no qualms about playing one group against the other . . . if we have separate meetings," the correspondent complained, and warned STG to be careful.¹⁵

Perhaps part of the problem was STG's lesser standing vis-à-vis Marshall as a full-fledged center. This aspect was improved in January 1960, when STG became a separate field element, reporting directly to the NASA Director of Space Flight Programs, Abe Silverstein. As Director of STG, Gilruth had his own staff of some 600, still physically located at Langley. With a new organizational structure and bureaucratic independence, STG was authorized to conduct advanced planning studies for manned vehicle systems, as well as to establish basic design criteria. STG also had authority to assume technical management of its projects, including the monitoring of contractors. By November, STG became even more independent when it was officially redesignated the Manned Spacecraft Center (MSC),¹⁶ and plans were being made to transfer MSC to its new location near Houston, Texas, by the middle of 1962.

It is interesting that Gilruth and von Braun's emissary, Eberhard Rees, soon thereafter were stressing the "equality" of the two NASA centers. Meeting in July 1961, the two men also agreed on setting up four joint panels to cope with the growing problems of design, hardware, operational, and bureaucratic coordination: Program Planning Scheduling; Launch Operations; Apollo-Advanced Vehicles; Apollo-Saturn C-1. Each panel, in addition, included certain working groups for specific areas, with provisions for ad hoc joint study groups as the need arose. For problems involving other NASA agencies, there were special technical liaison teams. In general, technically knowledgeable members were assigned on a functional, rather than an organizational, basis; wherever possible, the responsibilities of experienced personnel already assigned to internal working groups were increased.¹⁷

Naturally, all concerned hoped that the joint groups would promote understanding and reduce friction. That the Apollo-Saturn program succeeded as well as it did testifies to the value of such efforts, but this is

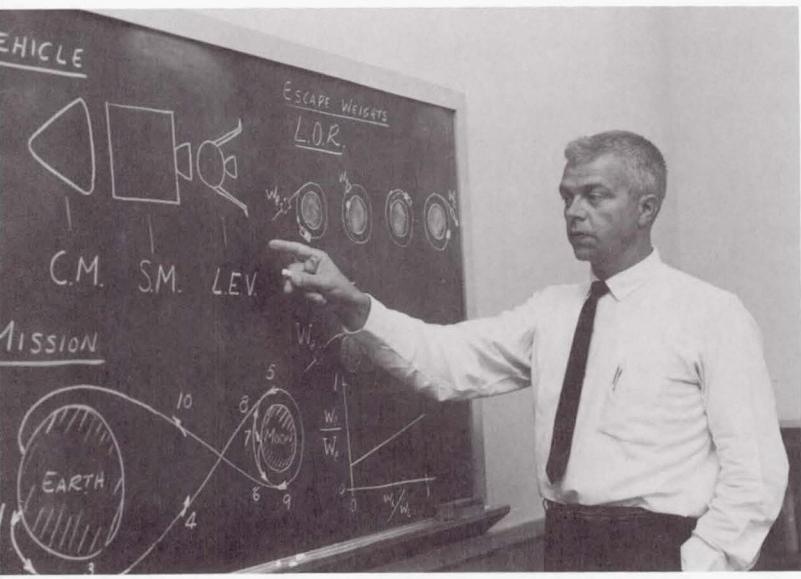
MISSIONS, MODES, AND MANUFACTURING

not to say that differences of opinion were always easily and quickly adjusted. The issue of EOR vesus LOR, for example, brought Marshall and the Manned Spacecraft Center into head-on conflict.

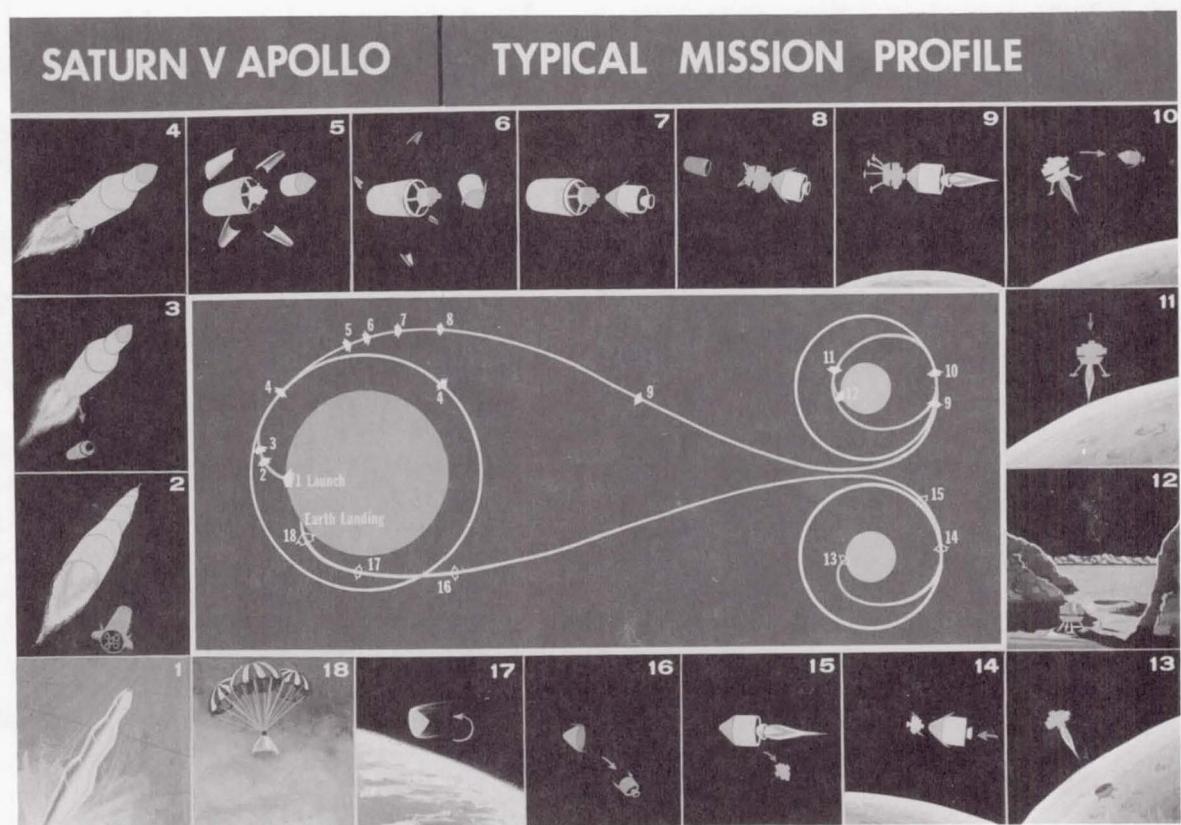
Early in 1961, NASA's studies for a manned lunar landing were keyed to the EOR mode using a Saturn vehicle or to direct ascent with the Nova.¹⁸ In view of MSC's later acceptance of LOR, Gilruth's initial support of the direct ascent concept is intriguing. "I feel that it is highly desirable to develop a launch vehicle with sufficient performance and reliability to carry out the lunar landing mission using the direct approach," he wrote to NASA Headquarters reliability expert Nicholas Golovin in the autumn of 1961. As for the rendezvous schemes (and here he apparently referred only to EOR), Gilruth said that they compromised mission reliability and flight safety, and that they were a "crutch to achieve early planned dates for launch vehicle availability, and to avoid the difficulty of developing a reliable Nova Class launch vehicle." At the same time, he understood the need for an Earth parking orbit during any mission to allow adequate time for final checkout of spacecraft, equipment, and crew readiness before going far from Earth.¹⁹

The concept of lunar orbital rendezvous (LOR) had been studied at Langley Research Center as early as 1960. The idea was passionately advocated by John Houbolt, a Langley engineer who first encountered it while investigating rendezvous techniques for orbiting space stations. The Langley-Houbolt concept of LOR was soon absorbed by the STG-MSC crew, and MSC eventually became the leading champion of LOR.²⁰ Houbolt played a key role in converting Headquarters planners to the LOR concept. Convinced that the idea had not received a fair hearing, Houbolt bypassed everyone and wrote directly to Associate Administrator Robert C. Seamans, Jr., in November. Fulminating at what he viewed as grandiose plans for using boosters that were too large and lunar landers that were too complex, Houbolt urged consideration of LOR as a simple, cost-effective scheme with high likelihood of success. "Give us the go-ahead, and a C-3," Houbolt pleaded, "and we will put man on the moon in very short order."²¹

Houbolt's letter apparently swayed several managers at Headquarters, especially George Low, Director of Space Craft and Flight Missions, in the Office of Manned Space Flight (OMSF). But D. Brainerd Holmes, who presided over OMSF, still had a prickly managerial problem. There remained people at Headquarters with doubts about LOR, principally Milton Rosen, newly named Director of Launch Vehicles and Propulsion in OMSF. Early in November, Holmes and Seamans directed Rosen to prepare a summary report on the large launch vehicle program, which of necessity dealt with the issue of EOR-LOR-direct ascent. The Rosen study came on top of several other committee reports on vehicles and



Left, John C. Houbolt goes through his chalk talk on the advantages of lunar orbit rendezvous over competing modes. Below, the typical mission profile using lunar orbit rendezvous.



MISSIONS, MODES, AND MANUFACTURING

landing modes. Rosen's group of 11 people, including 3 from MSFC (Willy Mrazek, Hans Maus, and James Bramlet), submitted its report on 20 November.²²

The issue of how to achieve a lunar landing at the earliest date became a principal theme in the Rosen group's deliberations. Although rendezvous offered an early possibility of a manned lunar landing, Rosen's working group noted that actual rendezvous and docking experience would not be available until 1964. LOR also seemed the riskiest and most tricky of the rendezvous modes, and the group expressed a decided preference for EOR. Either way, a C-5 Saturn with five F-1 engines in the first stage was the recommended vehicle. In spite of all the discussion of rendezvous, the Rosen committee in the end favored direct ascent as opposed to either EOR or LOR. "The United States should place primary emphasis on the direct flight mode for achieving the first manned lunar landing," the report flatly stated. "This mode gives greater assurance of accomplishment during this decade." Therefore, the Nova vehicle "should be developed on a top priority basis."²³ The trend toward LOR strengthened, however. Even though EOR became the "working mode" for budgetary planning for 1962, the debate went on.

Holmes hired Joseph Shea, an energetic young engineer, as Chief of the Office of Systems Engineering in OMSF, with responsibilities to conduct and coordinate mission mode studies. Holmes also instituted a top-level series of meetings under the rubric of "The Management Council," to discuss issues involving Headquarters and more than just one center alone.²⁴ At just about every meeting of the Management Council, Rosen and Gilruth got into a debate over the mode choice. Finally, as Rosen recalled, Gilruth came up to him after one of the meetings had adjourned and made one more pitch for the LOR mode. The most dangerous phase of the mission, Gilruth argued, was the actual landing on the moon. If Rosen's direct ascent idea was followed, then at the moment for lunar descent, that meant landing an unwieldy vehicle that was both quite long and quite heavy. A very touchy operation, Gilruth emphasized. LOR, on the other hand, boasted an important advantage: the lunar landing and lunar takeoff would be accomplished by a very light and maneuverable vehicle specifically designed for the task. Rosen confessed he had been preoccupied with simplicity from one end of the mission—the launch from Earth—and he had no convincing counterarguments when Gilruth made him look at simplicity from the other end, the lunar landing.²⁵

While the consensus at Headquarters now shifted towards LOR, the split between MSC and MSFC showed few signs of easing. On a swing through both MSC at Langley and MSFC at Huntsville in January 1962, Shea was discouraged by the entrenched position of the two centers: Marshall people displayed an "instinctive reaction" of negativism on the

STAGES TO SATURN

issue of LOR, while MSC personnel seemed too enthusiastic, even unrealistic, about rendezvous problems and the weight situation. Each center, Shea observed, intent on its own in-house studies, "completely ignores the capability of the other's hardware."²⁶ During the spring, however, MSC's research seemed to become more convincing. MSFC also began to regard LOR with increased interest. In mid-April, an MSC presentation at Huntsville elicited several favorable comments from von Braun himself.²⁷

The evidence suggests that von Braun increasingly felt the necessity of settling the issue so that they could get on with definitive contracts for launch vehicles and other hardware with long lead times.²⁸ Resolution of the EOR-LOR controversy finally came on 7 June 1962, when Shea and his aides were in Huntsville for still another session on the mode of rendezvous. In his concluding remarks, von Braun noted that the conference had given six hours of intensive analysis to various proposals, including Nova-direct as well as EOR and LOR. They all appeared to be feasible, von Braun commented; the problem was narrowing the choices to one and then acting on it. "It is absolutely mandatory that we arrive at a definite mode decision within the next few weeks, preferably by the first of July 1962," he declared. "We are already losing time in our overall program as a result of lacking a mode decision." Then von Braun announced that LOR was Marshall's first choice.

There were complex technological, economic, and administrative reasons for Marshall's ultimate decision to go along with LOR. Although von Braun elaborated on 11 principal reasons for choosing LOR, the basic consideration involved confidence that it provided the best chance for a successful manned lunar landing within the decade. The concept promised good performance margins. Separation of the lunar lander from the reentry vehicle seemed desirable from many considerations of design and operation, and the overall concept suggested good growth potential for both the lander and the booster. Von Braun also implied that both sides could work together without the potential friction of an "I told you so" attitude. The fact that he felt compelled to proffer such a verbal olive branch suggests that the heat generated by the EOR-LOR debate must have been considerable. The MSFC Director observed that "the issue of 'invented here' versus 'invented there' does not apply," because both MSC and MSFC, in effect, adopted an approach originally put forth by Langley. "I consider it fortunate indeed for the Manned Lunar Landing Program that both Centers, after much soul searching, have come to identical conclusions," von Braun emphasized. "This should give the Office of Manned Space Flight some additional assurance that our recommendations should not be too far from the truth."

Quickly ticking off the reasons for deciding against EOR, von Braun pointed out that it was still feasible. A looming negative factor was the double loss incurred if, for example, the tanker launch went just fine, but

MISSIONS, MODES, AND MANUFACTURING

the manned launch was postponed too long on the pad or had to abort during ascent, wiping out the mission to the cost of two complete launch vehicles and associated launch expenses. In addition, von Braun noted complex management and interface problems with dual launches. Using the C-5 in a direct launch posed some thorny technical problems and permitted only the thinnest margins in weight allowances for the spacecraft, so the C-5 direct route was rejected. The huge Nova booster could have solved some of these problems, but it was rejected principally because of its size, which would have created requirements beyond the existing scope of fabrication and test facilities available to NASA; there were also serious problems seen in time, funding, and technical demands for a booster of Nova's dimensions.²⁹

Even with von Braun's imprimatur in June, the irrevocable decision for LOR did not come until the end of 1962. The Huntsville conclave produced agreement at the center level only; NASA Headquarters still had to formalize the choice and implement the decision. Early in July, Seamans, Dryden, Webb, and Holmes concurred with a recommendation for LOR by the Manned Space Flight Management Council, but the President's Scientific Advisory Committee still actively questioned the LOR mode. The committee evidently preferred the EOR approach because it felt the technological development inherent in the EOR concept had more promise in the long run for civil and military operations; its argument also suggested that the LOR choice stemmed from internal NASA expediency—as the cheapest and earliest mission possibility—even though technical analysis of LOR was incomplete. Nicholas Golovin and Jerome Wiesner, in particular, remained adamantly against LOR, and the controversy actually boiled over into a public exchange between Wiesner and NASA officials at Huntsville while President Kennedy was touring Marshall Space Flight Center in September.

Host von Braun and the President were standing in front of a chart showing the LOR maneuver sequence. As von Braun proceeded to explain the details, Kennedy interrupted, "I understand Dr. Wiesner doesn't agree with this," and turned around to search the entourage of newsmen and VIPs around them. "Where is Jerry?" Kennedy demanded. Wiesner came up to join Kennedy and von Braun, with Webb, Seamans, and Holmes also in the group. Wiesner proceeded to outline his objections to LOR, and some lively dialogue ensued, just out of the earshot of straining newsmen and dozens of onlookers on the other side of a roped-off aisle. "They obviously knew we were discussing something other than golf scores," Seamans recalled. In fairness to Wiesner, Seamans later noted, the President's scientific advisor had to play the devil's advocate on many issues when a robust agency was vigorously pressing its position. Wiesner's job was to make sure that the President received alternative views, and he once confided to Seamans that he was



President Kennedy's visit to MSFC in September 1962 provided a forum for discussion of LOR: from the left, the President, MSFC Director Wernher von Braun, NASA Administrator James E. Webb, Vice-President Lyndon B. Johnson, Secretary of Defense Robert S. McNamara, and the President's Science Advisor Jerome B. Weisner.

not always comfortable in having to take negative points of view as Kennedy's advisor. Certainly, the LOR issue was one such example. As Seamans phrased it, "Here the President had his advisors recommending one approach, and the line operators recommending another." It was also one notable instance when Kennedy took a tack opposed to the PSAC position and supported NASA's decision for the LOR mode.³⁰

After a final round of studies, James Webb reaffirmed full commitment to LOR on 7 November and named a prime contractor, Grumman Aircraft Engineering Corporation, to build the lunar module.³¹ Thus, by the end of 1962, the outlines of the Apollo-Saturn program were firmly delineated, with agreement on a family of three evolutionary Saturn vehicles, a functionally designed spacecraft, a technique to land men on the lunar surface, and a technique to return them safely to Earth.

AN AEROSPACE EMPIRE

The Saturn program created a vast new aerospace enterprise, partly private and partly public, with MSFC directing a group of facilities whose extent far exceeded anything in the days of the old NACA. The federally owned facilities under Marshall's immediate jurisdiction eventually included the sprawling installation at Huntsville; the cavernous Michoud Assembly Facility (MAF) at New Orleans; the huge Mississippi Test Facility (MTF) at Bay St. Louis, Mississippi; and the Slidell Computer Facility at Slidell, Louisiana. Other government-owned facilities directly related to the Saturn program included the NASA Rocket Engine Test Site at Edwards

MISSIONS, MODES, AND MANUFACTURING

Air Force Base in California and the government-owned production facilities for the S-II second stage at Seal Beach, California.

The growth of Marshall Space Flight Center at Huntsville began almost as soon as the transfer of the von Braun team from the Army Ballistic Missile Agency in 1960. This shift involved some 4.8 square kilometers of land (within the 162 square kilometers of the Redstone Arsenal) and facilities valued at \$96 000 000, along with 4670 employees from ABMA's Development Operations Division. (For subsequent figures on manpower, plant value, etc., see the appendixes.) Settling in its new role, MSFC evolved as a facility of three distinct sectors, divided into an administrative and planning area, an industrial area, and test area. Although the transfer gave NASA the bulk of the land and facilities previously used by ABMA's Development Operations Division, von Braun's administrative staff was allowed to remain in their old ABMA offices on a temporary basis only, and a Saturn-sized test area was needed. Construction began on a new administrative complex and the first MSFC personnel took occupancy during the spring of 1963. Of the several approaches to the center, perhaps the most impressive was from the north. Driving several miles through the green pastures and wooded, rolling hills of the Alabama countryside, a viewer watched the administrative complex looming ever larger. Three multistory buildings were arranged in a "V" shape, with Building 4200, the tallest of the three, proudly riding the crest of a low hill. With the U.S. flag snapping smartly from its pole, this impressive office complex rising out of the rural landscape rarely failed to impress visitors. As director of the Marshall Space Flight Center, von Braun, with his staff, occupied office suites on the top two floors of Building 4200, irreverently known as the "von Braun Hilton."

Once over the crest of the hill, the visitor saw the rest of the Marshall complex stretching for several miles to the Tennessee River. In the foreground, the former ABMA laboratories and manufacturing areas occupied the equivalent of many city blocks. The labs incorporated facilities for a host of esoteric research projects, computation, astrionics, test, and other specialized research activities. Buildings for manufacturing, engineering, quality and reliability assurance, and others had cavernous, high bay areas attached to accommodate the outsized Saturn components. In the background, the skyline was punctuated by the silhouettes of the assorted test stands and other installations of the expanded test area. Here were the engine test stands, an F-1 engine turbopump test position, and two especially large installations visible for miles. One was the big, burly test stand for the S-IC first stage, 123 meters high, completed in 1964. The second was the Dynamic Test Stand, 129 meters high, designed to accommodate the complete Saturn "stack" of all three booster stages, the instrument unit, and the Apollo spacecraft. Inside the Dynamic Test Stand, heavy duty equipment shook

STAGES TO SATURN

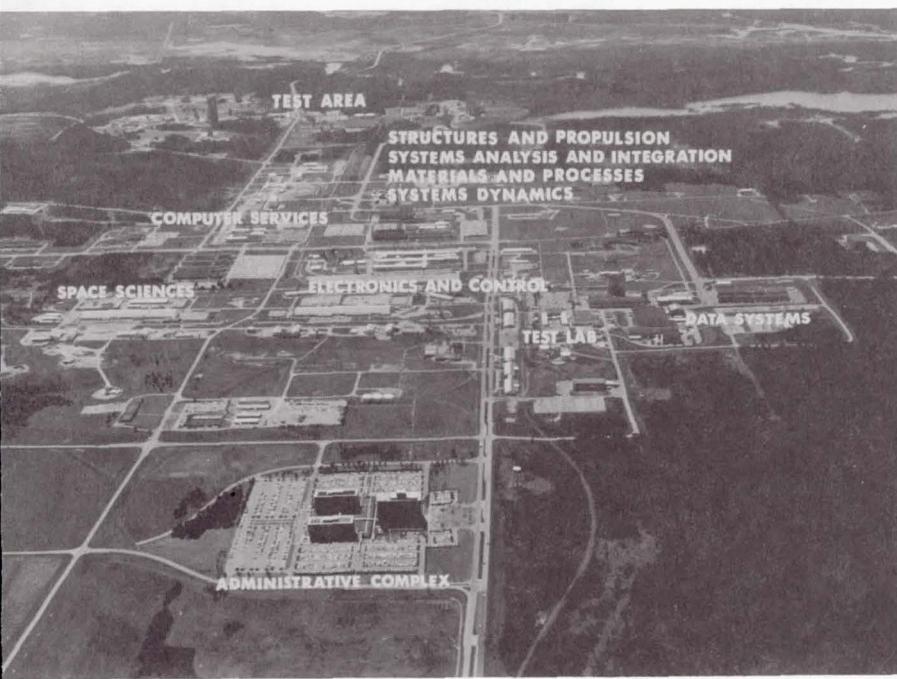
and pounded the vehicle to determine its bending and vibration characteristics during flight. Still further to the south, specially built roads for transporting the bulky Saturn flight stages led to docking facilities on the Tennessee River, where barges picked up or dropped off stages en route to other test sites or launch facilities at Cape Kennedy.³²

Except for the lawns and plantings around the administrative complex, Huntsville always had a factory look about it. Crisscrossed by streets and railroad tracks, Marshall still bore the stamp of its heritage as an Army arsenal, with lean, utilitarian structures, linked together by a web of electric and phone lines supported by ubiquitous poles. Buildings in the industrial area were frequently flanked by ranks of high-pressure gas bottles, cranes, hoists, and assorted large rocket components. A visit to the Manned Spacecraft Center at Houston, with its sleek, ultramodern office complexes and well-tailored inner courtyards (complete with ponds and rocky little streams) was a study in contrasts.

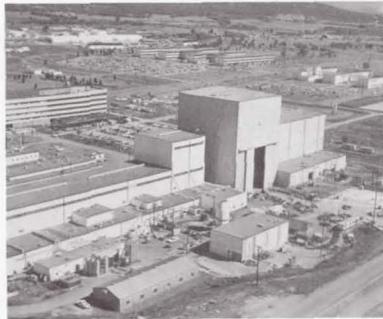
When Marshall was organized in 1960, the Army launch team under the direction of Kurt Debus became the Launch Operations Directorate, Marshall Space Flight Center. At the Army's Missile Firing Laboratory, the Debus team had been launching a series of Army vehicles, including Redstone and Jupiter, and had launched the first American Earth satellite, *Explorer I*. In the months following the transfer to NASA, they launched the manned Mercury-Redstone suborbital flights. As plans for the Saturn series were finalized, the Launch Operation Directorate, through Debus, participated in the search for a new launch site, large enough and removed far enough from population centers to satisfy the physical requirements of the big new space boosters. Cape Canaveral was chosen, and development of the new facilities began, with Launch Complex 34 becoming operational during the fall of 1961 to launch the first Saturn I vehicles.

The immense task of constructing new launch pads and developing the huge installations required for Saturn V operations called for a separate administrative entity. In March 1962, NASA announced plans to establish a new Launch Operations Center (LOC) at the Cape, and the change became effective on 1 July 1962. While close liaison continued, launch operations ceased to be a prime responsibility of MSFC, and Kurt Debus proceeded as Director, LOC, to develop the launch facilities for the Apollo-Saturn program.³³

Large as it was, the aerospace complex at MSFC could not begin to accommodate the escalating dimensions of the Saturn program. Consistent with its heritage as an Army arsenal with an extensive in-house capability, Marshall manufactured the first eight models of Saturn I's first stage and did the testing in its backyard. The physical size of other Saturn stages, the frequency of testing as production models came on line, and the sheer magnitude of the endeavor dictated the need for additional facilities located elsewhere. Each major contractor developed the



Left, an aerial view of Marshall Space Flight Center. Below, left to right, closeups of the Administrative Center, Propulsion and Vehicle Engineering Laboratory, and the test area (the three large stands are, from left, the F-1 engine test stand, Saturn V dynamic test stand, and the Saturn V booster stand).



special industrial capabilities required for the unique sizes inherent in the Saturn program, including fabrication, manufacturing, and testing. There was a certain kaleidoscopic aura about all these arrangements, since some were accomplished entirely by the contractor on privately owned premises and others were undertaken in government-owned facilities, with the contractor supplying most of the work force.

For example, the Saturn IB and Saturn V first stages were manufactured at the Michoud Assembly Facility (known familiarly as "Michoud") 24 kilometers east of downtown New Orleans. The prime contractors, Chrysler and Boeing, respectively, jointly occupied Michoud's 186 000 square meters of manufacturing floor space and 68 000 square meters of office space. The basic manufacturing building, one of the largest in the country, boasted 43 acres under one roof. By 1964, NASA added a separate engineering and office building, vertical assembly

STAGES TO SATURN

building, (for the S-IC) and test stage building (also for the S-IC). By 1966, other changes to the site included enlarged barge facilities and other miscellaneous support buildings. Two things remained unchanged: a pair of chimneys in front of the Administration Building, remnants of an old sugar plantation. These ungainly artifacts served as reminders of Michoud's checkered past, from a plantation grant by the King of France in 1763, to ownership by the wealthy but eccentric New Orleans recluse and junk dealer, Antoine Michoud. Never a successful plantation, its sometime production of lumber and other local resources from the swampy environs helped generate the local slogan, "from muskrats to moonships."

The plant itself dated back to World War II, when it was built to produce Liberty ships. A hiatus in contract agreements shifted the emphasis to cargo planes, but only two C-46 transports rolled out before the war ended. The government facility remained essentially inactive until the Korean War, when the Chrysler Corporation employed over 2000 workers to build engines for Army tanks. Dormant since 1954, the building had been costing the government \$140 000 per year to keep up. With so many jobs in the offing and the obvious level of economic activity to be generated by the manufacture of large rocket boosters, selection of the site occurred in a highly charged political atmosphere, with active lobbying by a number of congressmen and chambers of commerce from around the country. Eventual selection of the Michoud facility in 1961 followed a series of thorough NASA investigations, and Michoud easily fulfilled several high-priority considerations: production space and availability; location near a major metropolitan area; convenient year-round water transport facilities (to haul the oversized Saturn stages); and reasonable proximity to MSFC, the Cape, and a contemplated test-firing site for the finished stages.³⁴

The extent of computer services required for the activities at the Mississippi Test Facility and Michoud prompted MSFC managers to consider a major computer installation to serve both operations. Happily, a location was found that included a structure originally designed to support sophisticated electronic operations. At Slidell, Louisiana, 32 kilometers northeast of Michoud and 24 kilometers southwest of MTF, Marshall acquired a modern facility originally built by the Federal Aviation Administration. For modifications and installation of new equipment, MSFC spent over \$2 000 000 after acquiring the site in the summer of 1962. The array of digital and analog computers for test, checkout, simulation, and engineering studies made it one of the largest computer installations in the country.³⁵

In contrast to Michoud, where the plant facility sat waiting, the development of the Mississippi Test Facility became a contest with Mississippi mud—to say nothing of the poisonous snakes and clouds of mosquitoes that plagued construction workers. Although NASA began

MISSIONS, MODES, AND MANUFACTURING

with a list of 34 potential locations, the site for test-firing Saturn V rocket stages logically had to be close to the production facilities at Michoud and also be accessible by water for shipment of S-II stages. Other criteria quickly ruled out most of the other contending sites. The test area had to be big. Size was a safety factor; test sites had to be widely separated from critical support and supply facilities in case of accidental destruction of a stage during a test run. More important, at the time the test facility location was being debated, NASA designers were looking ahead to big, deep-space booster stages of up to 111 million newtons (25 million pounds) of thrust, and lots of noise. Therefore, a test area of expansive proportions was required but in a location where a minimum number of people would have to be relocated. After juggling all of these requirements, in October 1961 NASA settled on a sparsely populated corner of Hancock County, Mississippi. A new, \$300-million-plus space-age facility was hacked out of soggy cypress groves, Devil's Swamp, Dead Tiger Creek, and the Pearl River. By the intracoastal waterway and the Pearl River, MTF was only a 72-kilometer barge trip from the production facilities at Michoud, and was accessible by water to MSFC and the Cape.

The central test area, around the test stands, comprised 55 square kilometers, with a buffer zone of 518 square kilometers surrounding it. Approximately 850 families from five small hamlets were resettled outside MTF boundaries. The central test area was exclusively reserved for NASA use, and although the buffer zone was uninhabited, the area continued to be lumbered and teemed with wildlife, including wild hogs descended from abandoned farm stock. An employee picnic in 1967 frugally consigned some of these natural resources to a barbecue pit.³⁶

At the heart of MTF were the monolithic test stands: a dual-position structure for running the S-IC stage at full throttle, and two separate stands for the S-II stage. Laboratories, monitoring equipment, control center, and storage areas, including docks, were all deployed thousands of meters away. The MTF complex was tied together by 12 kilometers of canals (with navigation locks and a bascule bridge); 45 kilometers of railroads; and 56 kilometers of roads and paved highways. Under it all snaked 966 kilometers of cables, connecting test stands, laboratories, and data banks. Each month, MTF consumed enough electricity to keep 6000 households functioning.

An arm of MSFC at Huntsville, MTF had an administrative pattern that was a bit unusual. A comparatively small cadre of NASA personnel (about 100) carried out overall managerial and supervisory duties. This select group also made the final evaluation of test results and issued the flight-worthiness certificates to the stage contractors. Approximately 3000 contractor personnel made up the vast majority of the work force. North American and Boeing each had several hundred people running their respective test stands. The General Electric Company, with over 1500 people, had the contract for housekeeping services at MTF and

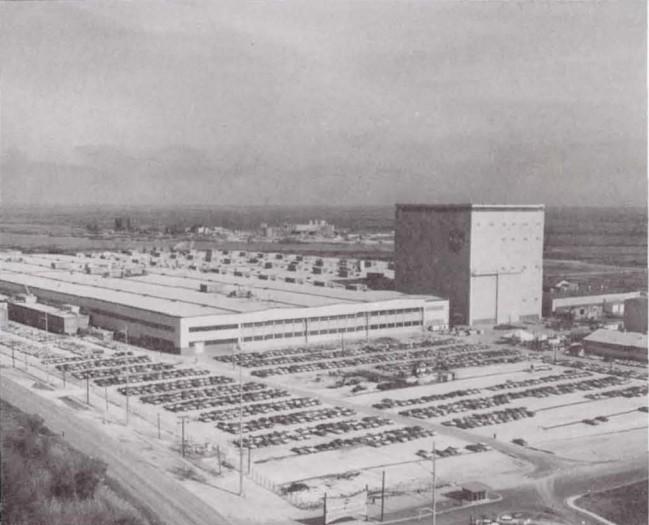
STAGES TO SATURN

provided maintenance for the facility and operational support at the test stands and elsewhere for the other tenants, including the construction firms. GE's range of support ran the gamut from 19 special items of cable equipment (for \$1 183 187), to the always popular snake bite kits (\$1.25 each). On occasion, GE hired cowboys to round up stray cattle in the outreaches of MTF, and it was GE that arranged for the transfer of the cemeteries during resettlement of the area's small towns.

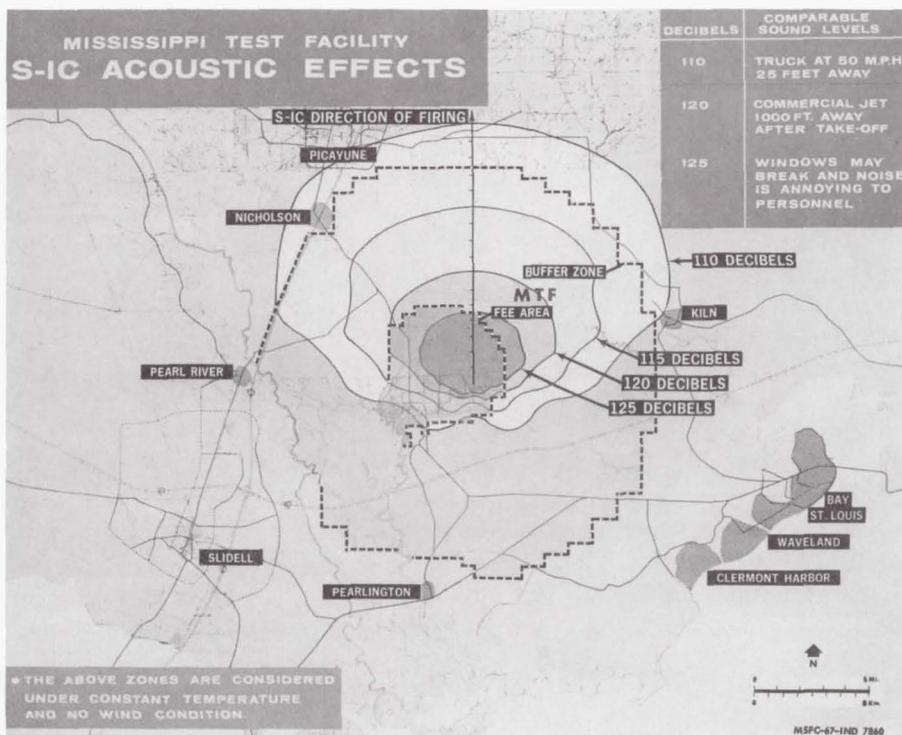
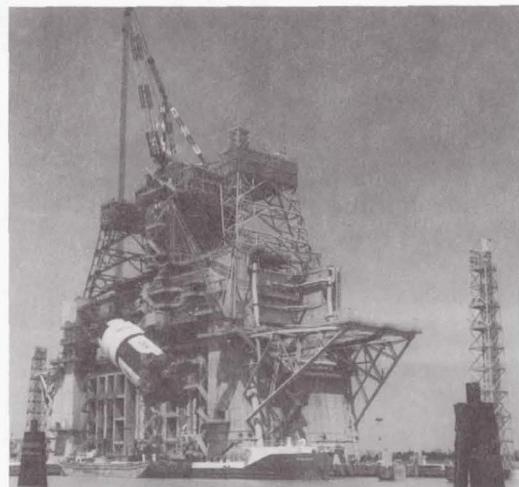
Development of MTF had a hectic air about it. Construction delays mounted by early 1964, after Mississippi went through a highly unusual cold snap and a snowstorm. Heavy rains came during January, topping records that had been on the books for 30 years. The schedules for construction and testing merged to the point where the first test firings in 1966 were being planned concurrently with ongoing construction. The MTF director, Jack Balch, observed: "We're sure this is the only way to do it, but for the next year we'll be riding with one foot on each of two galloping horses." The government-industry team at MTF did the job; the first stage-firing test a 15-second test of the S-II stage, was performed successfully on 23 April 1966 in the test stand designated A-2. On 3 March 1967, a 15-second test of the S-IC-T (test) stage activated the first-stage facility. In September 1967, the other S-II stand, designated A-1, was declared operational.³⁷

SATURN I AND IB AND THE LOWER STAGES

While these facilities were being developed, MSFC drew on experience, accumulated during the days of ABMA and the Army's arsenal concept, and developed the Saturn I—the vehicle originally designated as Juno V. On the threshold of starting to work on the large Juno V class of vehicles and other space hardware in 1959, Dr. Ernst Stuhlinger, von Braun's chief scientific advisor at ABMA, briefed NASA officials on the range of expected challenges and research required to develop vehicle components for space exploration. He noted the potential hazards from radiation, meteors, temperature extremes, and weightlessness. To cope with these environments, Stuhlinger stressed the need for research on a broad front, including special investigation into a list of 11 crucial materials and their current shortcomings in the space environment—from the decomposition of dielectrics and sealants, to unusual regimes of friction and wear for bearings and various moving parts, to the degradation of plastic and exposed surfaces, and to the vaporization and vacuum sticking of metals.³⁸ Specific investigation of these and other problems moved on parallel tracks with the integration of components and materials into the launch vehicle design, even while the launch vehicle itself was taking form on drawing boards and in machine shops.



Left, an aerial view of NASA's Michoud Operations. Below, the 124-meter-tall test stand at the Mississippi Test Facility is hoisting the first operational S-IC first stage for the Saturn V into test position. Bottom, the map shows the acoustic effects of an S-IC firing.



STAGES TO SATURN

Like most major development projects, the evolution of the Saturn I changed between conception and execution, although the configuration that emerged in 1958 was subjected to remarkably few major design variations before its first launch in 1961. The basic outlines for ABMA's concepts of the Saturn I (when it was still called Juno V) were sketched out in two reports to Advanced Research Projects Agency (ARPA) in October and November 1958; insights on various aspects of early design choices were provided by von Braun himself in ABMA's presentation to NASA in December 1958. For example, original concepts for yaw, pitch, and roll control called for hinged outer engines: two hinged for pitch; two hinged for yaw; all four for roll. But application of adequate control forces required fairly high deflection of the engine thrust vector, and the engine contractor (Rocketdyne) complained that this would put too much stress on propellant flex lines. Instead, gimbaling of all four outer engines was adopted, achieving adequate control force with less engine deflection. The gimbal system for mounting engines permitted each engine in the cluster to swivel about for either yaw or pitch control.

On the other hand, the original multiengine concept was maintained. Throughout the early design phase, ABMA stressed the reliability of the multiengine approach in case one or even two engines were lost. Particularly in the case of manned missions, von Braun emphasized, the engine-out capability offered much higher margins of safety in continuing a mission until conditions were less hazardous for separation of the crew capsule.

The multitank design also persisted as a design choice. In his NASA presentation, von Braun praised the multitank design for several reasons. Component tanks could be flown by Douglas C-124 Globemasters to any part of the world and reassembled for launch; this procedure would provide a high degree of flexibility. The separate tanks eliminated the technical difficulties of internal horizontal bulkheads, required in a large tank vehicle, to keep fuel and oxidizer separate. It also meant a shorter, and more desirable, vehicle. In spite of the added weight, most rocket propellant tanks included internal fuel slosh baffles, because splashing and surging of the liquid fuel created problems in keeping the vehicle stable and under control. In 1958, von Braun predicted that no fuel slosh baffles would be required in the multitank design because of the small diameter of the individual tanks (although the flight versions actually incorporated slosh baffles in their design). A great deal of attention was also given to booster recovery schemes, in which the spent first stage would be recovered from the ocean after its descent had been slowed by retrorockets and parachutes. The Huntsville group foresaw immense savings in the recovery scheme, since the illustration given by von Braun assumed "5 or 19 years from now" a launch rate of 100 vehicles per year over a 5-year period, at a cost of about \$10 million per launch.³⁹

MISSIONS, MODES, AND MANUFACTURING

More than any of the Saturn vehicles, the Saturn I S-I stage configuration evolved during flight tests (for details, see chapter 11). NASA developed the Saturn I as first-generation and second-generation rockets, designated Block I and Block II. The first four launches used the Block I vehicle, with inert upper stages and no fins on the first stage, the S-I. Block II versions carried a live second stage, the S-IV, sported a corolla of aerodynamic fins at the base, and used uprated H-1 engines. The S-I first stage for the Saturn I also became the first stage of the Saturn IB; in this application, it was called the S-IB. Again, there were modifications to the fins, engines, and various internal components. Nevertheless, the basic details of fabrication and testing of the Saturn I and Saturn IB remained similar. The first stage of the Saturn I and IB may have looked like a plumber's nightmare, but it fit the criteria of conservative design and economy established early in the program. As Marshall engineers discovered, development of a new booster of Saturn I's size involved a number of design problems. Fabrication of the tankage was comparatively easy. Even though the former Redstone and Jupiter tanks had to be lengthened from 12 to 16 meters to carry added propellants, the basic diameters of the 178-centimeter Redstone and 267-centimeter Jupiter tanks were retained, so they could be fabricated from the tooling and welding equipment still available at Huntsville. The tank arrangement settled on by MSFC gave an alternate pattern of the four fuel and four oxidizer tanks, clustered around the 267-centimeter center oxidizer tank. The oxidizer tanks carried the load from the upper stages of the Saturn, the fuel tanks only contributing to the lateral stiffness of the cluster. When filled, the oxidizer tanks contracted 63.5 millimeters, which meant that the fuel tanks had to have slip joints at their upper ends to accommodate other structural elements that fluctuated with the tank shrinkage. All together, the Saturn I first stage carried 340 000 kilograms of propellants in its nine tanks. To keep the propellant in one tank from depleting too rapidly during flight, which would seriously unbalance the vehicle, the Saturn I incorporated an interconnecting pipe system, with regulating equipment to keep propellants at uniform level in all tanks during a mission. Each of the four outboard fuel tanks fed two engines, yet interconnected with the other tanks. The 267-centimeter center liquid-oxygen (LOX) tank provided series flow to the four outboard LOX tanks, which also fed two engines apiece.

Although the group of tanks eased the potential slosh tendencies of a single large tank, each separate cylinder contained fixed baffles, running accordionlike down the tank interiors. Pressurization for the LOX tanks was done by a heat exchanger, dumping it into the top of the LOX tanks as gaseous oxygen. Gaseous nitrogen from fiberglass spheres at the top of the booster pressurized the fuel tanks. The 48 spheres fixed to the top of the stage were curiously reminiscent of bunches of grapes.

The cluster of tanks was held together at the base by the tail section

STAGES TO SATURN

and at the top by an aptly named structural component known as the "spider beam." The tail section consisted of the thrust structure assembly as well as the heat shield, shrouding for engine components, holddown points, stabilizing fins (on the later Saturn I first stages), and other components. Assembly of the spider beam required a special fixture for precise alignment and joining of the heavy aluminum I beams, of which it was made. Starting with a hub assembly, eight radial beams were attached to it at 45-degree intervals. Then eight more cross beams were joined to the outer ends of the radials with splice plates. The spider beam played a dual role. Special hardware attached to it was used during the initial clustering of the tanks. In other words, the spider beam served as an assembly fixture, then remained as part of the stage's permanent structural assemblies, with each outboard oxidizer tank affixed to the beam. Because a smaller diameter upper stage of 5.6 meters was planned for the Saturn I, an upper shroud was incorporated as part of the structural transition from the larger 6.5-meter-diameter first stage. The upper shroud also enclosed telemetry equipment, umbilical connection points used in ground test and launch preparation, and space for the recovery system for the first stage. In the later versions (the Block II models), the shroud section was eliminated, and instruments were housed in a separate instrument segment atop the upper stage. The recovery section was no longer required; additional studies, completed by early 1962, indicated that the recovery scheme would require extensive modification to the stage, so the idea was finally dropped.⁴⁰

In the process of refining the design of the Saturn I, two major problems emerged: stability and base heating. As with most large rockets, the Saturn I was highly unstable, with the overall center of gravity located on the heavy, lower-stage booster, while the center of lift, in most flight conditions, was high on the upper stages. The nature of the problem called for more advanced control processes than used on aircraft and rockets the size of ICBMs. The low natural frequency of the big vehicle was such that when the gimbaled engines moved to correct rocket motions, special care had to be taken not to amplify the motions because the control system frequency was close to that of the vehicle itself.

More worrisome, at least in the early design stage, was the problem of base heating. Even with a rocket powered by only one engine, the flow pattern at its base proved nearly impossible to predict for the various combinations of speed and altitude. Base heating occurred when the rocket exhaust interacted with the shock waves trailing behind the vehicle. This clash created unpredictable regions of dead air and zones of turbulent mixing. Heated by the rocket exhaust, the air trapped in these areas in turn raised the heat levels at the base of the rocket to undesirable temperatures. Worse, the fuel-rich exhaust flow from the engine turbopump could get caught in these "hot-spot" regions, causing fire or explosion.

MISSIONS, MODES, AND MANUFACTURING

The base heating phenomenon became worse with multiengine rockets. The eight-engine Saturn I cluster began to look like a Pandora's box of base heating. To get an idea of what to expect, and to work out some fixes ahead of time, the Saturn design team ran some cold flow tests, using scale-model hardware, and called on NASA's Lewis Research Center, in Cleveland, to run some unusual wind tunnel tests. These investigations involved a booster model with eight operating engines, each putting out 1100 newtons (250 pounds) of thrust. Following the tests and extensive theoretical studies, designers in Huntsville came up with several ideas to cope with the base-heating situation. Arranged in a cross-shaped configuration, the engine pattern of the cluster was conceived to minimize dead air regions and turbulent zones. The four inner engines were bunched together in the center to reduce excessive heating in the central area, and the remaining four were positioned to avoid structural interference as the gimbaled engines swung on their mounts. The lower skirt was designed to direct large streams of high-energy air toward the four center engines in particular to prevent dead air regions from developing in their vicinity. A heavy fire wall was installed across the base of the booster near the throat of the engines, with flexible engine skirts to permit gimbaling and, at the same time, keep the super-heated gas from flowing back up to the turbopumps and propellant lines above. The problem of the exhaust from the turbopumps received special attention. For the four center engines, which were fixed, the fuel-rich exhaust gases were piped to the edge of the booster skirt and dumped overboard into a region of high-velocity air flow. In later vehicles, the exhaust gases were dumped exactly into the "centerstar" created by the four fixed engines. The gimbaled outboard engines required a different approach. The turbopump was fixed to the gimbaled engines; therefore an overboard duct for them would have required a flexible coupling that could withstand the high temperatures of the turbine exhaust gases. Instead, MSFC devised outboard engine attachments called aspirators, which forced the turbine exhaust into hoods around the engine exhaust area and mixed the turbopump exhaust with the engine's main exhaust flow.⁴¹

Successful ignition and operation of an eight-engine cluster of Saturn's dimensions required extensive testing beforehand. In December 1958, ARPA released funds for modifications to one side of a two-position Juno test tower in order to test-fire the Saturn I first stage. Preparations for these static tests, as they were called, required extensive reworking of the Saturn's side of the tower, including a new steel and concrete foundation down to bedrock, a steel overhead support structure and a 110-metric ton overhead crane, a new flame deflector and fire-control system, and much new instrumentation. The job took a whole year. By January 1959, ABMA crews installed a full-sized, high-

STAGES TO SATURN

fidelity mockup of the first stage in the tower to check all the interfaces for service and test equipment. Satisfied, they took the mockup out, and put in the first static-test version. The test booster, SA-T, was installed during February, and late in March the first firing test, a timid one, burned only two engines for an eight-second run. Many skeptics still doubted that the eight-engine cluster would operate satisfactorily. "People at that time still had a lot of difficulty persuading individual rocket motors to fire up . . . reliably," von Braun explained, "and here we said we would fire up all eight simultaneously." There were a lot of jokes about "Cluster's Last Stand," von Braun chuckled. Still, the firing crew at Marshall proceeded cautiously. Not until the third run, on 29 April 1960, did test engineers fire up all eight barrels, and then only for an eight-second burst. By the middle of June, the first stage was roaring at full power for more than two minutes.

Reverberations of the Saturn tests were quickly felt. The acoustical impact was quite evident in the immediate area around the city of Huntsville, and the long-range sound propagation occurred at distances up to 160 kilometers. The result was a rash of accidental damage to windows and wall plaster, followed by a rash of damage claims (sometimes filed by citizens on days when no tests had been conducted). Aware that climatic conditions caused very pronounced differences in noise levels and long-range sound propagation, engineers began taking meteorological soundings and installed a huge acoustical horn atop a tower in the vicinity of the test area. No ordinary tooter, the horn was over 7.6 meters long and had a huge flared aperture over 4.6 meters high. Its sonorous gawps, bounced off a network of sound recorders, gave acoustical engineers a good idea whether it was safe to fire the big rockets on overcast days.⁴²

To make the most use of the expensive test facilities, as soon as a booster completed its test-firing series and was shipped off to Cape Canaveral for launch, the SA-T booster was fastened back into place for further verification and testing of Saturn systems. The complex test instrumentation was complemented by the growing sophistication of automatic checkout systems used in the Saturn I first stage. Early hardware was designed for manual checkout. As more advanced electronics and computers became available, significant portions of the procedure were designed for automatic tests and checks. The scope of automatic test and checkout evolved into a complex network that tied together diverse geographic test and manufacturing locations. Later generations of Saturn vehicles and individual components were electronically monitored, literally, from the time of the first buildup on the shop floor until the mission was finished in outer space.

Because manufacturing tests of individual stages occurred separately at diverse locations, a specialized facility was required to verify the

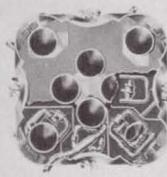
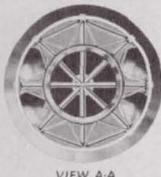
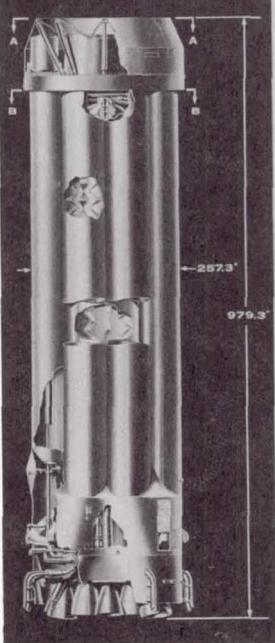
MISSIONS, MODES, AND MANUFACTURING

physical interface design, system integration, and system operation of the total vehicle. During a flight, natural structural frequencies occurred—the result of vibrations of moving parts, aerodynamic forces, and so on. If the control-force input of gimbaling engines, for example, reinforced the structure's natural frequency, the amplification of such structural deflections could destroy the vehicle. So a dynamic test stand, large enough to surround a complete two-stage Saturn I, was begun at MSFC in the summer of 1960 and finished early in 1961. The dynamic test facility was designed to test the vehicle either in entirety or in separate flight configurations. Vibration loads could be applied to the vehicle in pitch, yaw, roll, or longitudinal axis to get data on resonance frequencies and bending modes. Saturn I tests uncovered several problem areas that were then solved before launch. Matching frequencies in the gimbal structure and hydraulic system were uncovered and "decoupled." Static tests revealed weaknesses in the heat-shield curtains around the engines, so the flexible curtains were redesigned. Structural failure of the outer liquid-oxygen tanks required a reworking of the propellant flow system.⁴³

Historically, the style of ABMA operations emphasized in-house fabrication and production, as Army arsenals had traditionally done. As the scale of the Saturn program increased, MSFC made the obvious and logical choice to turn over fabrication and manufacture to private industry. At the same time, the center retained an unusually strong in-house capability, to keep abreast of the state of the art, undertake preliminary work on new prototype hardware, and to make sure that the contractor did the job properly (for management details, see chapter 9). The do-it-yourself idea was most strongly reflected in the development of the Saturn I first stage. Ten Saturn I vehicles were built and launched; the first eight used S-I first stages manufactured by MSFC, although the fifth flight vehicle carried a contractor-built second stage (the Douglas S-IV). The last two Saturn Is to be launched had both stages supplied by private industry. Douglas supplied the S-IV upper stage, and the Chrysler Corporation's Space Division supplied the S-I lower stage.

Late in the summer of 1961, while the first Saturn I was en route to Florida for launch, MSFC began plans to select the private contractor to take over its S-I stage. The manufacturing site at Michoud was announced on 7 September, and a preliminary conference for prospective bidders occurred in New Orleans on 26 September. The first Saturn I was launched successfully one month later (27 October), and on 17 November, Chrysler was selected from five candidates to produce the S-I first stage. The final contract called for the manufacture, checkout, and test of 20 first-stage boosters. Chrysler participated in the renovation of Michoud as it tooled up for production. In the meantime, the shops at Marshall turned out the last seven S-I boosters, progressively relinquishing the primary production responsibility. During December 1961, for example,

SATURN S-I STRUCTURE



Saturn I

Left, the drawing of the Saturn I S-I stage shows the multitank configuration. The cutaway shows the fuel baffles inside the tanks. Below, in MSFC's Fabrication and Engineering Laboratory an S-I is being assembled. The two end spider beams are connected to the central 267-centimeter-diameter liquid-oxygen tank; the first of the eight 178-centimeter outer tanks, used alternately for liquid oxygen and kerosene, is being lifted into position.



MSFC manufactured its last 1.78-meter and 2.67-meter tanks, turning over this job to Chance-Vought, of Dallas, which supplied both MSFC and Michoud as Chrysler took over the booster production.⁴⁴

Chrysler, a major automotive manufacturer, was no novice to the production of rockets, having worked with the von Braun team since

MISSIONS, MODES, AND MANUFACTURING

1954 producing Redstone rockets and their successor, the Jupiter. Chrysler easily shifted from the Saturn I to the larger Saturn IB. In July 1962, when NASA announced its intention to use the lunar orbit rendezvous, the space agency also released details on the two other Saturn vehicles. The three-stage Saturn V was planned for the lunar mission. A corollary decision called for development of an interim vehicle, the Saturn IB, to permit early testing of Apollo-Saturn hardware, such as the manned command and service modules, and the manned lunar excursion module in Earth orbit, as well as the S-IVB stage of the Saturn V. This decision permitted such flight testing a year before the Saturn V would be available. Chrysler's initial contract, completed late in 1962, called for 13 first-stage Saturn IB boosters and 8 Saturn I first-stage boosters.⁴⁵

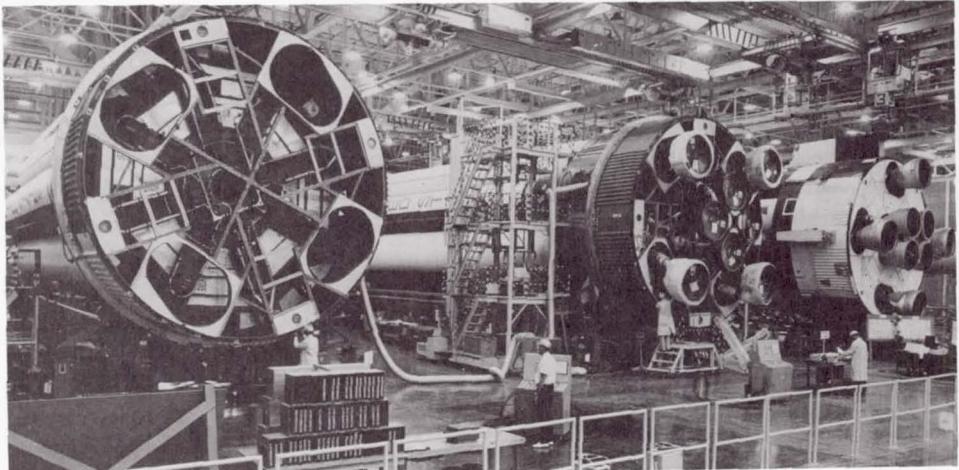
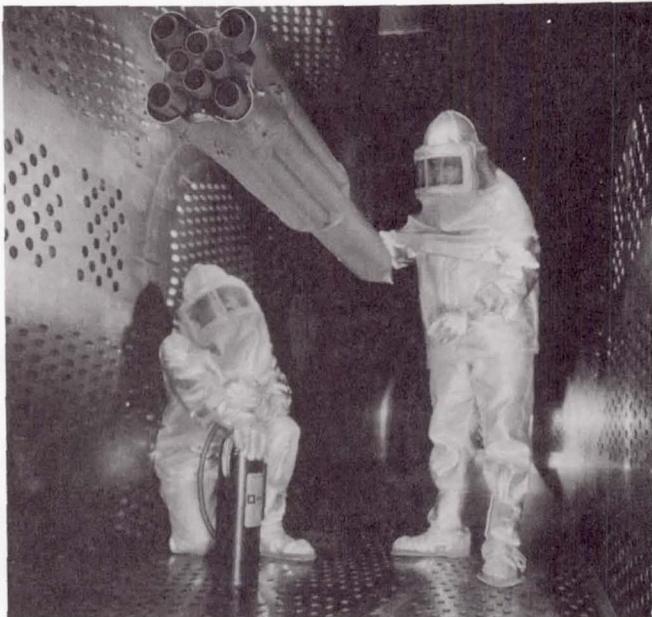
In most respects, the new S-IB first-stage booster retained the size and shape of its S-I predecessor. The upper area was modified to take the larger-diameter and heavier S-IVB upper stage, and the aerodynamic fins were redesigned for the longer and heavier vehicle. The Saturn IB mounted its eight H-1 engines in the same cluster pattern as the Saturn I, although successive improvements raised the total thrust of each engine to 890 000 newtons (200 000 pounds) and then to 912 000 newtons (205 000 pounds). The thrust increase raised the overall performance of the Saturn IB; the performance was further enhanced by cutting some 9000 kilograms of weight from the stage cluster. A more compact fin design accounted for part of the reduction, along with modifications to the propellant tanks, spider beam, and other components and removal of various tubes and brackets no longer required. Additional weight savings accrued from changes in the instrument unit and S-IVB, and the insights gained from the operational flights of Saturn I. Many times, engineers came to realize designs had been too conservative—too heavy or unnecessarily redundant. The production techniques worked out for the Saturn S-I stage were directly applicable to the S-IB, so no major retooling or change in the manufacturing sequence was required. With so few basic changes in the booster configuration, existing checkout and test procedures could also be applied. At Huntsville, appropriate modifications were made to the dynamic test stand to account for the different payload configurations of the Saturn IB and the same static test stand served just as well for the S-IB first stage, although engineers reworked the stand's second test position to accept additional S-IB stages.⁴⁶

SUMMARY

During 1961–1962, several crucial decisions were completed to clarify configurations of the Saturn program and to agree on the mode to land astronauts on the moon. Once the idea of direct ascent via a Nova

Saturn IB

Right, engineers in a Lewis Research Center wind tunnel are aligning a model of the Saturn IB prior to firing tests to determine the amount and distribution of base heating from the blast of the eight engines. Below, three Saturn IBs are in various stages of assembly at Michoud.



vehicle was discarded, the major issue became Earth orbital rendezvous or lunar orbital rendezvous. One of the last holdouts against LOR, Marshall eventually opted for it because it averted the multiple launches of an EOR sequence and offered the best chances for a successful mission before the end of the 1960s.

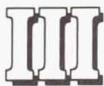
Once the issue of the mission profile had been settled, the task of developing the resources for manufacturing and testing of the Saturns became paramount, and engineers finalized the design of the Saturn I's first stage, which evolved into the first stage of the Saturn IB as well.

At this point, in the early 1960s, development of the Saturn I and IB loomed large in press releases and news stories, with special attention on

MISSIONS, MODES, AND MANUFACTURING

the lower stages. The work in this area set the baselines for manufacturing procedures, static firing tests of the multibarrel cluster, and the first launches of the Saturn I, with a live lower stage and a dummy upper stage. Because NASA and MSFC planners put such special emphasis on early static-firing tests of each stage, the engines had to be ready. From the beginning, MSFC maintained a strong effort in research, development, and production of Saturn propulsion systems. Meanwhile, parallel work on other hardware of the Saturn program proceeded: R&D on the upper stages for the Saturn I and IB (to be modified for the Saturn V); R&D for the first two stages of the mammoth Saturn V; plans for unique tooling required for production and fabrication; schemes for guidance and control of the launch vehicle. The main effort leading to large launch vehicles for manned lunar voyages was just beginning to build momentum.

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Fire, Smoke, and Thunder: The Engines

The H-1 engine traced its ancestry to postwar American development of rocket propulsion systems, and the opening section of chapter 4 includes an assessment of this engine's technological heritage. While the development of other engines discussed in Part Three differed in specifics, the overall trends in their design, test, and achievement of operational status paralleled that of the H-1 and sprang from the same evolving technology. Introduced on the Saturn V, the giant F-1 engine, while more akin to the conventional cryogenics of the H-1, experienced many development problems. The problem of scale affected many aspects of Saturn hardware development, as the F-1 story attests.

Application of liquid hydrogen (LH_2) technology constituted one of the key aspects of Apollo-Saturn's success. The upper stages of the Saturn I and Saturn IB introduced LH_2 -fueled RL-10 and J-2 engines, respectively, as discussed in chapter 5.

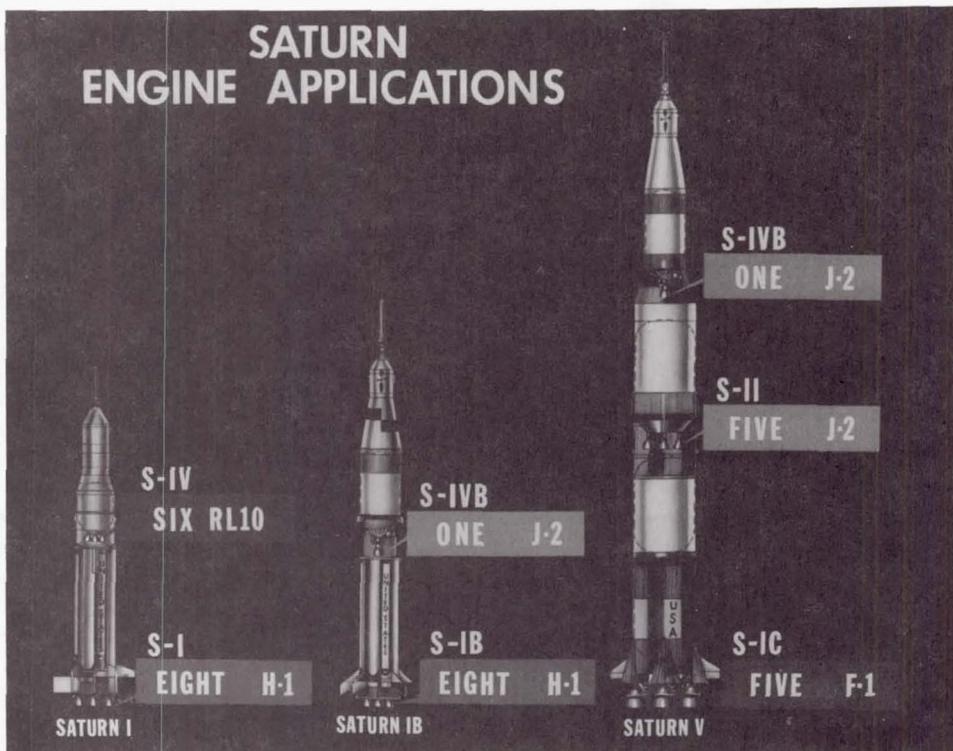
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4

Conventional Cryogenics: The H-1 and F-1

Development of rocket engines was usually conducted several steps ahead of the stage's tankage and the stage itself. This was done because of the inherent complexities of propulsion systems and inherent difficulties in engine research and development. Moreover, the choice of engine propellants influenced many elements of stage design, including the location of fuel and oxidizer tanks, propellant lines, and the various subsystems involved in the interface between the engine and stage.

Much of the ultimate success of the Saturn launch vehicles depended on the application of cryogenic technology—the use of liquefied gases in propellant combinations. The first-stage engines of the Saturn I, Saturn IB, and Saturn V (respectively, the S-I, S-IB, and S-IC stages) used a noncryogenic fuel called RP-1, derived from kerosene. All Saturn's engines used liquid oxygen as the oxidizer, and the engines of the S-IV, S-IVB, and S-II stages relied on liquid hydrogen as fuel. Put simply, the ability to carry large amounts of cryogenic propellants meant much more efficient launch vehicles. If designers had tried to build a rocket large enough to carry gaseous propellants, the size and weight of the tanks would have made it impossible to construct and launch such a vehicle. With the gaseous propellants converted to a liquid state, requiring less volume, designers had the opportunity to come up with a design capable of getting off the ground. In the 1960s, cryogenic technology experienced a phenomenal rate of growth and state of development. In support of the space effort, scientists and engineers accomplished a number of major breakthroughs, not only in the field of cryogenics itself, but also in the design and production of cryogenic rocket engines.



CRYOGENIC TECHNOLOGY

The scope of cryogenics was neatly summarized in a NASA report on cryogenics and space flight:

Cryogenics is the discipline that involves the properties and use of materials at extremely low temperatures; it included the production, storage, and use of cryogenic fluids. A gas is considered to be cryogen if it can be changed to a liquid by the removal of heat and by subsequent temperature reduction to a very low value. The temperature range that is of interest in cryogenics is not defined precisely; however, most researchers consider a gas to be cryogenic if it can be liquefied at or below -240° F. The most common cryogenic fluids are air, argon, helium, hydrogen, methane, neon, nitrogen, and oxygen.¹

In the early post-World-War-II era, as the United States' military services struggled to develop their own stable of launch vehicles, they leaned very heavily on the German wartime experience in technical areas

CONVENTIONAL CRYOGENICS: H-1 AND F-1

beyond the basic design of vehicles and rocket engines. Although a reasonable amount of cryogenic technology was available in the United States by World War II, there was little experience in applying it to rocketry. Goddard's work in cryogenics was apparently overlooked or inappropriate to the scale demanded by the ICBM program.

The development of the intercontinental ballistic missile (ICBM) required a host of subsidiary technological advances, in such areas as cryogenic fluid systems, insulation, handling and loading propellants, and large storage dewars. As some American experts admitted later, "Initially, the basic V-2 cryogenics data were used because the data constituted the sole candidate for consideration at the time." Eventually, the United States built up its own storehouse of cryogenic technology for rocket development. The ICBM program and other research by civilian agencies prompted greater interest for governmentally supported research, and the Cryogenic Laboratory of the National Bureau of Standards in Boulder, Colorado, opened in 1952. By that date, cryogenics was firmly established as an industrial and research discipline, ready to support military requirements and the American space programs, particularly in the 1960s.²

SATURN ENGINE ANTECEDENTS

The role of cryogenics in American launch vehicles increased steadily, starting with the liquid-oxygen oxidizer of the Vanguard first stage. Other rockets like the Redstone (and its derivatives), Thor, Atlas, Titan I, and finally the Apollo-Saturn series of launch vehicles—the Saturn I, Saturn IB, and Saturn V—used cryogenic oxidizers, fuels, or both.³ As in so many engineering achievements, engine development for the Saturn program represented the culmination of earlier R&D efforts, as well as the improvement of earlier production items. The large vehicle boosters of the Saturn program borrowed liberally from the accumulated engine technology of the ICBMs and the intermediate range ballistic missiles (IRBMs) developed for the military, particularly the Thor and Jupiter IRBM programs as well as the Atlas ICBM.⁴ The H-1 traced its general lineage to no less than five prior designs: the control valves, gas generator system, turbopump assembly, and thrust chamber derived specifically from hardware applied in the Thor, Jupiter, and Atlas engine.⁵

Thrust increased dramatically, from the 120 000 newtons (27 000 pounds) of Vanguard's first stage in 1959 to the 33 000 000-newton (7 500 000-pound) first-stage booster of the Saturn V in 1967. The fantastic jump in thrust levels was accompanied by gains in the specific impulse (a measure of efficiency of a rocket propellant, equal to the amount of thrust obtained per pound of propellant burned per second),

STAGES TO SATURN

especially with the introduction of liquid-hydrogen engines on the upper stages of the Centaur and Saturn launch vehicles, a major achievement of the American space program. Concurrently, advances were essential in a number of supporting technologies—lightweight components, compact packaging, materials application, and fabrication procedures. Propulsion system designers and engineers accumulated considerable experience along the way and refined various elements of the engine for better operation and introduced more sophisticated components and better control systems. Taken together, a myriad of improvements through research and development after the end of World War II contributed to higher levels of good engine design, with higher specific impulses, thrust stability, and flexibility in operational status.⁶

A review of engine advances achieved by the mid-1960s can effectively characterize the accomplishments leading up to the Saturn and highlight the innovations that were actually incorporated into the Saturn propulsion systems. Problem areas, which limited the desired performance of these engines, received special attention from a wide variety of research programs. Many improvements stemmed from the research programs carried out by industry. Many more evolved from the cooperative efforts generated by NASA and the various military services. The primary technological advances can be summarized under the following categories: thrust chambers, turbopumps, and system design and packaging.

THRUST CHAMBERS

Many early liquid-propellant engines featured a conical nozzle. Engineering improvements in thrust chambers were aimed at more efficient shapes for increased performance and decrease in weight. Designers sought higher performance through higher area-ratio shapes with higher chamber pressures to minimize the size and weight of the thrust chamber. In the drive to produce large, high-pressure engines, a major hurdle was a satisfactory means to cool the thrust chamber. An early solution used double-wall construction; cold fuel passed through this space en route to the combustion chamber, thereby reducing the temperature of the inner chamber wall. But design limitations restricted coolant velocity in the critically hot throat area of the engine. Thin-walled tubes promised an ideal solution for the problem of the thrust chamber walls. Tubes reduced wall thickness and thermal resistance and, more importantly, increased the coolant velocity in the throat section to carry off the increased heat flux there. As chamber pressures continued to go up along with higher temperatures, designers introduced a variable cross section within the tube. This configuration allowed the tube bundle to be fabricated to the desired thrust chamber contour, but variations in the tube's cross section (and coolant velocity) matched the heat transfer at various points along the tube. The bell-shaped nozzle permitted addi-

CONVENTIONAL CRYOGENICS: H-1 AND F-1

tional advantages in reducing size and weight when compared with what engineers called the "standard 15-degree half-angle conical nozzle." Without any reduction in performance, the bell shape also permitted a 20 percent reduction in length.

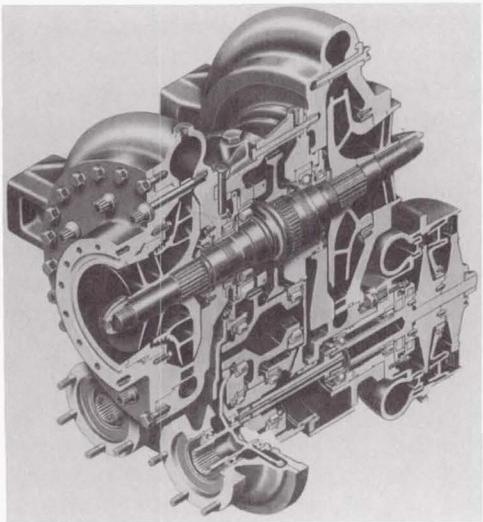
TURBOPUMPS

Advances in one area of the propulsion system created demands on other parts of the system. As thrust levels and pressures increased, so did demands on the turbomachinery to supply propellants at greater flow rates and higher pressures. Problems concerned the development of higher powered turbomachinery without increases in size or weight. Advances in turbomachinery design centered on higher speeds, and the goal of higher speeds encouraged the introduction of rotating components with smaller diameters. Essential subsidiary improvements dealt with high-speed bearings, the performance of high-speed inducers, and higher speeds for the impeller tips. Engineers succeeded in increasing the operating speed of bearings through minute attention to details of the operating environment and the fabrication of bearing parts. Designers reconsidered and redesigned bearings for their optimum size, the contact angle of surfaces touching the bearing, and the curvature of the race structure. Better performance was gained by engineering the newly designed bearings for combating contact fatigue and wear from overheating. Further refinements included the introduction of new, high-strength materials and improved surface finishes in the fabrication of precision parts. The innovative use of the engine's own propellants as "lubricants" was another advance. Although the propellants were not lubricants in the usual sense, they served the same purpose. The properties of the propellant-lubricants were more important in carrying off frictional heat to keep pump bearings cool and operable. This application simplified turbopump operation and eliminated the need for externally supplied lubrication.

Engine designers also attacked propellant cavitation, a condition in which the formation and collapse of bubbles or vapor pockets while pumping the propellant caused vibrations and damage to rocket machinery. Study programs found how the cavitation characteristics were related to the inducer through such minute factors as the angle of blades, taper, blade sweep, and the profile of the leading edge. More accurate theories on the phenomenon of cavitation enabled a redesign of the inducers that doubled their suction. The overall increase in suction efficiency of the turbopump permitted the pump to operate at higher speeds. This contributed to weight savings in the vehicle because tank pressures—and tank weight—could be lowered. The higher operating speeds and pressures triggered development of pump impellers to

STAGES TO SATURN

operate with higher tip speeds. The infusion of high-strength materials, plus design improvements and fabrication techniques paid off in reliability and greater speed. In total, all of these developments enhanced the incremental gains in power-to-weight ratios.



This cutaway drawing of the turbopump for the H-1 engine shows the back-to-back arrangement of oxidizer pump (at left end) and fuel pump (at right end) operating off a common turbine and gear box (center). The propellerlike inducer blades can be seen on the left end of the shaft.

PACKAGING AND SYSTEM DESIGN

Over a brief span of time, the packaging and design of cryogenic rocket engines made dramatic progress. The size of the thrust chamber increased, while the "packaging" (pumps, turbomachinery, and related systems) remained relatively constant or actually decreased in physical size. At the same time, efficiency and design advantages accrued. In the early Redstone days, builders situated the turbopump, propellant lines, and controls above the thrust chamber and achieved directional control by the use of jet vanes. When gimbaled (movable) thrust chambers appeared on the scene, the design limitations of pumps, lines, and other paraphernalia dictated their attachment to the more solid footing of the vehicle's thrust structure. With the thrust chamber as the only movable part of the engine, engineers had to develop a new high-pressure feed line, with great flexibility, to link the propellant pumps to the thrust chamber. As the rise in chamber pressures and thrust levels put increased strains on the high-pressure lines, designers began studies of systems design and packaging to permit mounting the turbopump and associated gear onto the thrust chamber itself. In this configuration, the pump and chamber could be gimbaled as a single unit, permitting the installation of

CONVENTIONAL CRYOGENICS: H-1 AND F-1

low-pressure "flex lines" between the pump inlets and the vehicle tanks. As it so happened, improvements in the design and efficiency of turbomachinery already made it compact and reliable enough to justify relocation on the thrust chamber.⁷

PREDICTABLE ENGINE PROBLEM PHASES

In many ways, the H-1 was a composite example of rocket engine development in the 1950s, modified and improved for its role in manned launches of the Saturn I and Saturn IB. Even though the H-1 was derived from a propulsion system already in production (the S-3D engine for the Thor and Jupiter), requirements for increased thrust and generally improved performance led designers and engineers into new and frustrating problems. The evolution of both the H-1 and the F-1 engines fell into the pattern of many launch vehicle development programs, in which the engines constituted the pacing item.⁸ Furthermore, the difficulties in engine design were usually predictable, as Leonard C. Bostwick, a veteran MSFC engine manager, knew all too well. "The development of liquid rocket engines followed similar patterns regardless of engine size," he asserted. Despite this ability of the engine managers to look with a crystal ball into the future, ability to avoid all expected pitfalls did not follow. "In the development of liquid rocket engines, problems occur at several distinct intervals," Bostwick continued. "The type of problem and the time phase can be predicted, but since the exact nature of the problem cannot be so readily defined, a five to seven year development program becomes a necessity."⁹ In general, an engine development program progressed through four distinct "problem phases" over the five- to seven-year period.

The designers of each successive generation of rocket engines commenced their work with facts and figures accumulated—often painfully—from earlier designs and experience. If, however, the new engine was expected to perform better than the old ones, the designers very quickly found themselves in uncharted territory. They proceeded to push ahead of the state of the art, seeking more flexibility in operations, greater simplicity, increased thrust, and improved overall performance. At this point, Bostwick pointed out, "The first problem phase occurs because of the inability to totally extrapolate and build on existing knowledge." Just as problems were predictable, so were the problem areas. Bostwick was specific: "The problems will occur in the combustion mechanics, propellant movement, or in the propellant control system." The hardware evolved for this early development period often proved to be less than adequate, and faults would sometimes not show up until the engines moved past the initial firing sequence tests, perhaps in the late tests to maximum projected duration and thrust levels. When the

STAGES TO SATURN

problems then showed up, they were "often catastrophic," Bostwick wryly observed. For this reason, the engines were subject to extensive test programs to expose their inherent frailties.

Some time after the engine had successfully passed qualification tests of the basic engine design, or even the preflight rating trials, the second cycle of problems appeared. The difficulties involved the mating of the propulsion systems to the vehicle or stage. Because the development of the engines usually preceded the development of the stage by two or three years, the engines would not fit the mounting hardware and multitudinous connections with the stage. In addition, there were the peculiarities of late changes in the stage-engine interface requirements or possibly in the operational environment introduced by new variations in the flight plans. The stage contractors received prototypes or preflight-rated engines and cooperated with the engine interface. Inevitably, new sets of variables, which could not be anticipated from mating with a nonexistent stage or for changes in mission requirements, created problems.

As the engines phased out of the developmental stage and into full production, MSFC personnel and the manufacturer turned their attention to the third round of problems. They watched the elements of quality control, tolerances in the manufacturing of components, vendor selection, choice of manufacturing materials, and definition of the integral manufacturing process. "A continuing development program is planned during the period," Bostwick explained, "to provide the trained personnel, facilities and hardware capabilities, to investigate these problems and to prove out the required corrective effort."

Defying all these attempts to identify potential failures, to uncover and correct weaknesses before a multimillion-dollar vehicle left the launch pad, actual missions inevitably uncovered a fourth set of problems, because there was no way to duplicate the actual environment in which the vehicle had to perform. With launch dates carefully scheduled ahead of time to coincide with the launch "windows" and carefully paced to the requirements of the Apollo-Saturn program, the problems uncovered by one mission demanded a very fast response to keep the next phase of the program on schedule. For this reason, NASA and the contractors maintained a well-staffed cadre of specialists at the contractors' engineering and test facilities, backed up by the facilities available at MSFC.

With the four major problem phases successfully handled, the need for ongoing development and engineering monitoring continued. "When engine systems are tested to longer durations and more extreme limits," warned Bostwick, "problems are uncovered that may have existed for a long time but were not evident until the more severe testing on a larger engine sample produced the failure mode." Other factors entered the picture too, such as changes in process, improvements in manufacture, or

CONVENTIONAL CRYOGENICS: H-1 AND F-1

changes in vendors, any or all of which could create a problem in quality of the hardware or introduce a different and incompatible material.¹⁰

Despite the best intentions of all concerned, engine development and production encountered predicaments throughout the duration of the Saturn program.

THE H-1 ENGINE: MILESTONES AND FACILITIES

With requirements for the first generation of Saturn launch vehicles established in general terms, planners began to consider the development of propulsion systems. To save time and money, NASA opted for an effort firmly rooted in existing engine technology. The result was a decision to modify the Thor-Jupiter engine, the 667 000-newton (150 000-pound) thrust S-3D and uprate the engine to a thrust of 836 000 newtons (188 000 pounds). On 11 September 1958, NASA awarded the contract for the uprated engine to Rocketdyne, the original supplier of the S-3D engines for Thor and Jupiter. In the beginning, engineers designed the H-1 for a clustered configuration to gain higher thrust than could be obtained from any existing single engine. The basic concept featured four fixed inboard engines and four outboard engines with gimbal mounts to provide attitude control for the vehicle.¹¹

Although the original specifications called for 836 000 newtons (188 000 pounds) of thrust, the first models were delivered at 734 000 newtons (165 000 pounds) of thrust—down rated for greater reliability. Eventually, the H-1 engine served the first Saturn vehicles in four separate versions: 734 (165)-, 836 (188)-, 890 (200)-, and 912 000 newtons (205 000 pounds) of thrust. Saturn I used the 734 (165) and 836 (188) engines in clusters of eight; Saturn IB mounted eight units of the 890 (200) model in vehicles SA-201 through SA-205, with the 912 (205) model earmarked for SA-206 and subsequent vehicles. The engines all had the same approximate dimensions, standing 218 centimeters high, with a radius of 168 centimeters at the throat. The H-1 engines incorporated a tubular-walled, regeneratively cooled thrust chamber. The propellant was supplied by twin pumps, driven through a gearbox by a single turbine, which was powered in turn by a gas generator burning a mixture of the vehicle's main propellants.¹²

Because the engine's basic design was kept to existing components and propulsion systems, Rocketdyne got off to a running start; the first 734 000-newton (165 000-pound) thrust prototype came off the drawing boards, was put together in the contractor's shops, and static-tested by 31 December 1958, less than four months after the contract was signed. Development proceeded rapidly; by the spring of 1960, NASA had performed the initial test of the eight-engine cluster, and the H-1 passed the Preliminary Flight Rating Tests by the fall of the same year. These

STAGES TO SATURN

milestones demonstrated the basic ability of this version of the H-1 to meet the flight requirements, and on 27 October 1961, vehicle SA-1 was launched successfully. Close on the heels of the 734 000-newton (165 000-pound) thrust engine, NASA and Rocketdyne initiated work on more powerful models; intended for later Saturn I missions, the 836 000-newton (188 000-pound) version of the H-1 went through its preliminary flight-rating test on 28 September 1962.¹³

For the S-IB first stage of the Saturn IB launch vehicle, MSFC began studies for uprated engines with Chrysler, the first-stage contractor. In November 1963, Chrysler returned its analysis of engine load criteria and suggestions to mesh the schedules for engines and stages. On this basis, MSFC directed Rocketdyne to go ahead from the more powerful 890 000-newton (200 000-pound) thrust engine to a 912 000-newton (205 000-pound) thrust system for the most advanced missions contemplated for the Saturn IB. The schedule for engine deliveries stretched out through 1968, when, on 30 June 1967, Rocketdyne signed a contract calling for a final production batch of 60 H-1 engines, bringing the total number purchased to 322.¹⁴

Testing for the H-1 engine occurred in several widely separated areas. Initial development took place in the engineering facilities at Rocketdyne's main plant in Canoga Park, California. In the nearby Santa Susana Mountains, the company used one engine test stand, known as Canyon 3b, for early development testing. For component testing, single-engine tests, and clustered-engine tests, the H-1 program depended on facilities located at Marshall Space Flight Center in Huntsville. Installations at MSFC for H-1 development included a component testing laboratory, a gas generator test stand, a single-engine test stand, and a full-sized booster test stand for engine cluster tests. At Rocketdyne's primary manufacturing complex for the H-1, located in Neosho, Missouri, the company relied on existing installations for manufacture and acceptance testing. Two dual-position test stands were available, built for the original purpose of checking out engines manufactured for Air Force missiles. A rental agreement, negotiated by NASA and the Air Force, permitted Rocketdyne to use one position on each of the dual stands.¹⁵

THE H-1 ENGINE: GENERAL DESCRIPTION

The models of the H-1 used in the Saturn I and Saturn IB shared the same seven major systems: thrust chamber and gimbal assembly, exhaust system, gas generator and control system, propellant feed system, turbopump, fuel additive blender unit, and electrical system. Production of the H-1 propulsion system involved several design aspects unique to the Saturn program. For example, the Saturn H-1 engine came out of Rocketdyne's shops in two slightly different models. Each unit had a gimbal assembly for attachment to the vehicle, but the inboard engines,

CONVENTIONAL CRYOGENICS: H-1 AND F-1

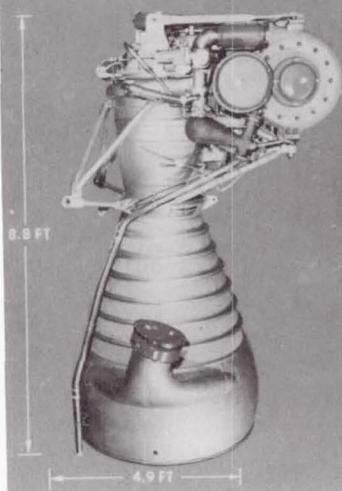
not required for thrust vector control, were immobilized by struts which held them rigidly in place. The outboard engines were equipped with gimbal actuators, attached to outriggers on the thrust chamber, that produced the gimbaling action for directional control for the vehicle. Basically identical, the inboard and outboard engines possessed an additional physical difference that necessitated a different label for each. The exhaust system varied for the outboard and inboard engines, although both types mounted a turbine exhaust hood, a turbine exhaust duct, and a heat exchanger (with a coil system to convert liquid oxygen to the gaseous oxygen required to pressure the oxygen tanks). The H-1C engine, the fixed inboard unit, had a curved exhaust duct to carry the turbine exhaust gases, and the H-1D engine, the gimbaled outboard unit, mounted a unit known as an aspirator. The inboard engines simply ducted the turbine exhaust overboard. The outboard engine exhaust was ducted into collectors, or aspirators, located at the exit plane of the nozzle. For the H-1D aspirator, designers chose a welded Hastelloy C shell assembly, mounted on the outside of the thrust chamber and extending beyond the thrust chamber exit plane. The aspirator prevented the fuel-rich exhaust gases of the gas generator from recirculating into the missile boat tail during flight. Instead, the gases merged into the engine exhaust plume.

As developed for the Saturn program, the H-1 also shed a number of accessories carried over from the Jupiter engine system. Early versions of the H-1 relied on the Jupiter's lubrication system, which featured a 73-liter (20-gallon) oil tank. The H-1 designers arranged for the vehicle's own fuel, RP-1 (along with some additives), to do the same job. This arrangement eliminated not only the oil tankage, but also a potential source of contamination. The new approach required a fuel additive blender unit as part of the engine system, tapping RP-1 fuel from the fuel turbopump discharge system. During development, the H-1 shed other remnants of its heritage from the Jupiter. A single-engine ballistic missile needed complex thrust controls to ensure its accurate impact on target. The Jupiter, perforce, carried considerable ancillary baggage to accomplish its mission—pressure transducers, magnetic amplifiers, hydraulic servo valves, and a throttling valve for the gas generator and liquid oxygen. The H-1 engine, by contrast, relied on simple, calibrated orifices within the engine, because thrust control requirements were much less severe when individual engines were clustered. In the Saturn, this permitted a marked simplification of the H-1, accompanied by an attendant gain in reliability.¹⁶

THE H-1 ENGINE DEVELOPMENT PROBLEMS

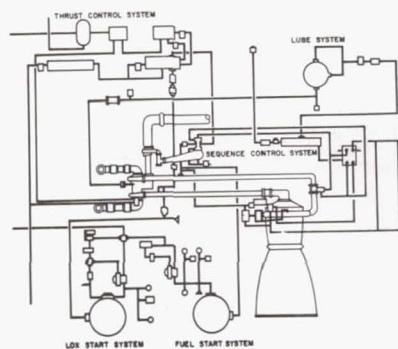
Lee Belew, manager of the Engine Program Office at MSFC, noted four major development problems during the H-1 era. These included

H-1 ENGINE

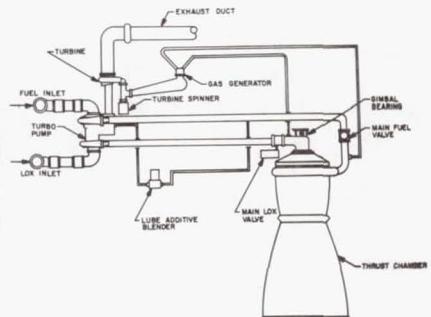


	VEHICLE EFFECTIVITY SA-201 THRU SA-205	SA-206 & SUBSEQUENT
THRUST (SEA LEVEL)	200,000 LB	205,000 LB
THRUST DURATION	155 SEC	155 SEC
SPECIFIC IMPULSE (LB-SEC/LB)	260.5 MIN	261.0 MIN
ENGINE WT DRY (INBD)	1,830 LB	2,100 LB
(OUTBD)	2,100 LB	2,100 LB
ENGINE WT BURNOUT (INBD)	2,200 LB	2,200 LB
(OUTBD)	2,200 LB	2,200 LB
EXIT-TO-THROAT AREA RATIO	8 TO 1	8 TO 1
PROPELLANTS	LOX & RP-1	LOX & RP-1
MIXTURE RATIO	2.23±2%	2.23±2%
CONTRACTOR: NAA/ROCKETDYNE		
VEHICLE APPLICATION		
SATURN IB/S-IB STAGE (EIGHT ENGINES)		

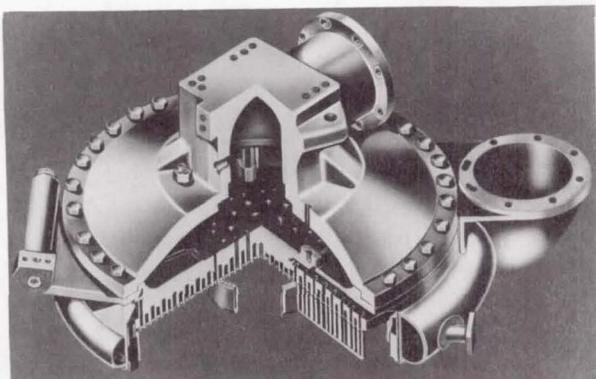
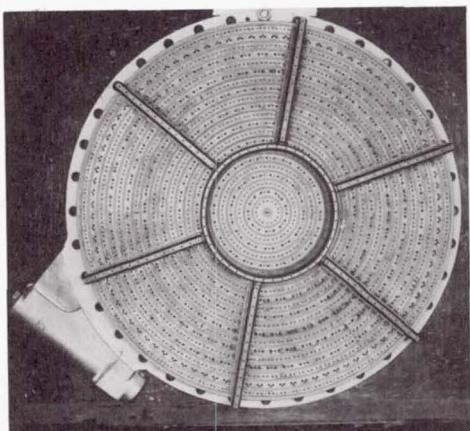
JUPITER S-3D ENGINE SYSTEM



SATURN H-1 ENGINE SYSTEM



The H-1 engine statistics are shown at the top; the sketch above shows the drive for simplification of the H-1 engine from its parent S-3D. Below, left, is the H-1 injector plate and at right is the H-1 liquid oxygen dome bolted in position above the injector.



CONVENTIONAL CRYOGENICS: H-1 AND F-1

combustion instability (or combustion oscillation, as he called it), cracks in the liquid oxygen dome, thrust chamber tube splitting, and problems with the pump gears and bearings. Other difficulties made their appearance, and each required a different kind of troubleshooting to solve the case.

The term "combustion instability" described an unsteady or abnormal combustion of fuel, a condition that not only reduced engine performance, but could destroy the engine—and the rocket as well. Within NASA and contractor circles, there was early concern about the potential problem of combustion instability, particularly in the uprated engines for Saturn I and the even larger engines planned for the Saturn V. Investigators deliberately set out to introduce combustion instability in the H-1 to see if the engine could recover, and if not, redesign the engine to overcome this potential danger. Late in 1963, a research group evolved a technique to induce combustion instability. Workers fixed a special boss to the face of the injector, and attached a small, 50-grain bomb to it. Enclosed in a cylindrical nylon case designed for initial cooling by engine fuel, the bomb was protected during engine start and run up but soon heated up, and after a time, it ignited. The explosion disturbed the combustion flame front sufficiently to create an unstable operating condition. It was hoped that the injector could recover from the instability in less than 0.1 second, but the Thor-Atlas injectors, uprated to 836 000 newtons (188 000 pounds) of thrust, failed to effect recovery in 8 of 16 bomb tests. After some research and development work, designers rearranged the injector orifices and added some baffles to the face of the injector. The new design worked beautifully, giving satisfactory recovery at various thrust levels and an unexpected bonus—an actual increase in engine performance.¹⁷

Another problem required changes in several flight vehicles. While vehicle SA-7 was undergoing a series of leak checks at Cape Kennedy in the fall of 1964, technicians came across a crack in the LOX dome of an H-1 engine mounted on the first stage. An investigation team traced the weakness to stress corrosion of the aluminum alloy, which called for replacement of the domes on all eight engines. Fortunately, a new type of aluminum alloy dome with much higher resistance to stress corrosion had already been developed. Rocketdyne also introduced a new dome manufacturing process that included an additional heat treatment, as well as additional machining of the finished part prior to the anodizing process. The dome cracks henceforth disappeared.¹⁸

Difficulties encountered with the tubular-wall thrust chamber exposed some of the problems encountered in the process of uprating a proven engine system to higher thrust levels, from 734 000 newtons (165 000 pounds) of thrust to 836 000 newtons (188 000 pounds) of thrust. Early in 1962, test engineers reported an alarming frequency of longitudinal splits in the tubes of the regeneratively cooled thrust chamber. Not only

STAGES TO SATURN

was this condition a hazardous condition and a hindrance to engine performance, but investigators also suspected that problems of combustion instability could be traced to fuel spraying embrittlement of the nickel-alloy tubes, a shortcoming that did not appear in the 734 000-newton (165 000-pound) engine because it operated at lower temperatures. In the hotter operating regimes of the 836 000-newton (188 000-pound) thrust engine, researchers discovered that sulphur in the kerosene-based RP-1 fuel precipitated out to combine with the nickel alloy of the thrust chamber tubes. The result: sulphur embrittlement and failure. The "fix" for this deficiency in the new uprated engine involved changing the tubular thrust chamber walls from nickel alloy to stainless steel (347 alloy), which did not react with sulphur.¹⁹

At frequent intervals, MSFC and contractor personnel met together to discuss such problems and to consider solutions. At one such meeting, on 1 December 1966, the debate turned to three recently developed problems and included continuing consideration on a report about miscreant materials used in the manufacture of turbine blades. Convening in the conference room of the Industrial Operations Division of MSFC, the participants included technical personnel and management representatives from MSFC, Chrysler (the stage contractor), and Rocketdyne (the engine contractor). Chrysler and Rocketdyne led off the session, with commentary about the discovery of a dozen chunks of Teflon material behind the injector plate of No. 4 engine on the S-IB-7 stage. Workers at Chrysler (who had first discovered the problem) gathered up the 12 shards of Teflon and pieced them together into a flat shape about 5 centimeters square, with some nondescript markings. Representatives from Rocketdyne's Neosho facility, where H-1 manufacturing was concentrated, went to work to discover the origin of the intruding flotsam. While this analysis progressed, related data hinted at similar anomalies in other engines of vehicle S-IB-7. The Rocketdyne spokesman presented data on engine No. 4 that revealed differences in its performance during recent static testing as compared with previous testing—no doubt because of the Teflon pieces obstructing the propellant flow. Rocketdyne was now concerned about two more engines. The No. 8 engine had performance data that paralleled No. 4 in some respects, suggesting a second Teflon interference problem, originating from one of the liquid-oxygen tanks. Moreover, the plumbing sequence in S-IB-7 caused the conferees to suspect that loose pieces of Teflon, originating from a particular liquid-oxygen tank, could also be lodged in the No. 5 engine system as well. The conference group agreed that engines No. 5 and No. 8 posed potential dangers and should be detached and opened up for thorough inspection, despite the impact on launch schedules.

Luckily, soon after the conference, Solar Division of the International Harvester Company, an H-1 subcontractor for valve components and other fittings, found the source of the Teflon pieces. During some of

CONVENTIONAL CRYOGENICS: H-1 AND F-1

its welding operations, Solar used Teflon buffers to protect the weld piece from abrasions caused by clamps. In fabrication and welding of flexible joints in the liquid-oxygen line, Solar surmised, one of the Teflon buffers could have slipped inside the line. They presented a sample of the buffer, which had the same general markings, size, and shape as the original culprit. With the source of the problem localized, MSFC and contractor officials agreed to call off the plans to inspect the other engines, and the case of the Teflon intrusion was closed, although some stricter fabrication and handling procedures went into effect.

The December 1966 conference took up other details affecting the Saturn program, such as steel filings that lodged, thankfully, in the mesh filter of the lubricating system for No. 6 engine sometime during short-duration firing tests on S-IB-8. The safety screen had done its job. Still, the discovery of loose filings anywhere in the Saturn's lubrication system or propellant system raised the specter of disaster. Chrysler, the stage contractor, was charged with finding the source of the loose filings. The conference also discussed a frozen turbine shaft of the No. 6 engine on S-IB-8. After a round of charges and countercharges, the group found that personnel from all three parties involved (Rocketdyne, Chrysler, and NASA) had conducted an engine test without conforming to written procedures. Conference officials agreed on closer enforcement and possibly new guidelines to prevent recurrences.²⁰

The final problem taken up by the December 1966 meeting—the turbine blades—involved the inadvertent substitution of the wrong material during manufacture. During a “hot test” (actually firing the propellants) on a Saturn IB first stage, one of the H-1 engines experienced failure of turbine blades. After the engines were removed and dismantled, the defective blades were found to have been cast from 316 stainless steel rather than the Stellite 21 material specified in the production orders. An error at Haynes Stellite (a division of Union Carbide) created the mix-up. Although the quality control procedures employed x-ray analysis of each blade for flaws, penetration of welds, and differences in materials in a production batch, the x-ray check could not catch this particular mistake if all the blades were of the wrong material. Revelation of the error came late in 1966, when the Haynes Stellite plant in Kokomo, Indiana, was in the grip of a strike. The strike, of course, made communication between MSFC and Haynes Stellite personnel more difficult. Concern about the substandard turbine blades extended beyond NASA—the slip probably extended to blades in engines supplied for Thor and Atlas missiles. The turbine blade imbroglio not only compromised the Apollo-Saturn program, it shadowed the capabilities of the national defense as well.

Knowing that defective blades existed in H-1 and other engines, investigators from Rocketdyne and MSFC went to work devising a system to identify the culprits without pulling all eight engines from every S-IB

STAGES TO SATURN

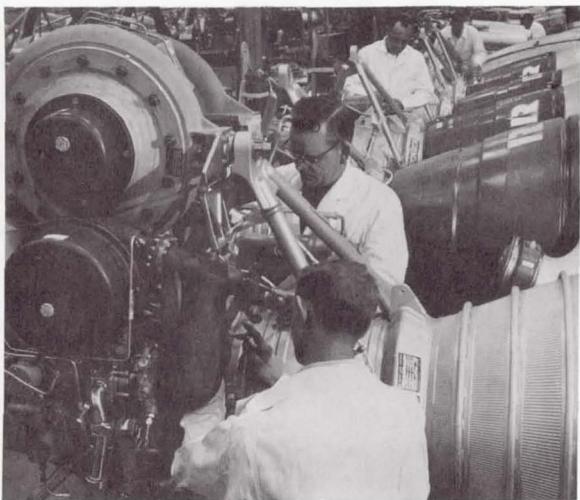
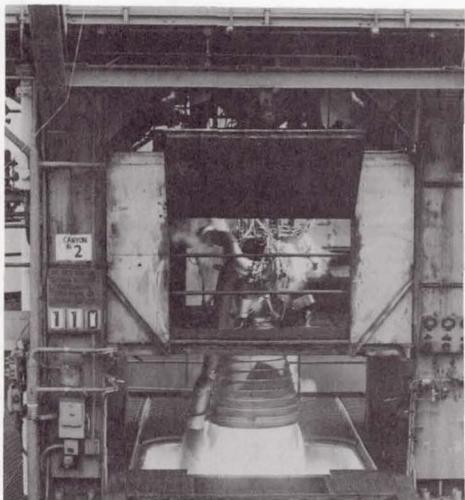
stage in the NASA stable, as well as military missiles, and laboriously tearing them down for lab analysis. As the strike at Haynes Stellite persisted, NASA and MSFC relied on official leverage to get representatives from Rocketdyne into the Haynes Stellite plant to find out what really happened. To the limit of its ability under the circumstances, Haynes Stellite cooperated, and the company itself came up with an "eddy current" machine to help in the detective work. Properly calibrated, this handy unit could differentiate between Stellite 21 material and the undesirable 316 stainless steel. Applied to Saturn propulsion systems, the investigation tracked down 10 H-1 engines with alien turbine blades. Workers pulled all 10 engines from the stages and replaced the turbine wheels with new units, followed by a hot fire of each repaired engine to verify its performance and reliability. In addition to preventive measures instituted at Rocketdyne and MSFC, the contractor added to the inspection procedures an identification by alloy type of each mold that was poured and set up reference standards to catch variations in density during the x-ray examination. In addition, every blade was tested for hardness, and a sample of the vendor's shipments of turbine blades was subjected to a wider array of metallurgical tests.²¹

With this kind of quality control and inspection, the H-1 engines experienced only one serious problem in 15 launches of the Saturn I and Saturn IB. During the flight of SA-6 in May 1964, one engine shut down prematurely. The vehicle's "engine-out" design proved its worth, as the mission continued to a successful conclusion. Based on information transmitted during the flight, analysts located the failure in the power train, "somewhere between the turbine shaft and the C-pinion in the turbopump." The incident was not entirely unexpected: prior to the flight, a product improvement team had already developed an improved power train design. In fact, starting with vehicle SA-7, the new units had already been installed.²²

The development of the H-1 represented a case study of predictable engine problem phases, as outlined by MSFC engine specialist Leonard Bostwick. True to form, the larger F-1 experienced similar growing pains. If these travails seemed more acute, they reflected the size of a much more substantial engine.

ORIGINS OF THE F-1

Not long after its formation in 1958, NASA decided to opt for a "leapfrog" approach in high-thrust engines, instead of the traditional engineering procedure of measured step-by-step development. This decision was bolstered by Russian successes in lofting large orbital payloads into space and also by recent U.S. plans for circumlunar missions and manned excursions to the moon. NASA's contract award to



At left is shown a 1963 test firing of an H-1 engine on a Rocketdyne test stand. At right are H-1 engines in Rocketdyne's assembly line at Canoga Park, California.

Rocketdyne in 1959, calling for an engine with a thrust of 6.7 million newtons (1.5 million pounds), was a significant jump beyond anything else in operation at the time. Executives within the space program looked on the big engine as a calculated gamble to overtake the Russians and realize American hopes for manned lunar missions. It seemed within the realm of possibility too, by using engine design concepts already proven in lower thrust systems and by relying on conventional liquid oxygen and RP-1 propellants.²³

The F-1 engine had roots outside NASA: the big booster came to the space agency in 1958 as part of the Air Force legacy. The F-1 engine, developed by Rocketdyne, dated back to an Air Force program in 1955. NASA carefully husbanded this inheritance during the transfer of projects to the fledgling space agency, so that no inconsiderable amount of Air Force expertise, along with voluminous reports, came with the engine. NASA then conducted its own feasibility studies and Rocketdyne received, in effect, a follow-on contract in 1959 to step up work on the gargantuan propulsion system.²⁴

At that time, no vehicle existed to use the F-1. In fact, no designated mission existed either. Even though engine development was undertaken with no specific application in mind, this approach was not unprecedented. The complexities and uncertainties in the evolution of propulsion systems encouraged their prior development. This situation, while not out of the ordinary, did lead to some of the first design problems of the F-1. When Boeing was selected as prime contractor for the first stage of an advanced version of the Saturn in December 1961, the configuration

STAGES TO SATURN

of the vehicle was still uncertain. Not until 10 January 1962 did NASA confirm that the advanced Saturn (named Saturn V in February) would have a first stage (the S-IC stage) powered by five F-1 engines. Since the engine's application was not known at first, designers and engineers tried to anticipate reasonable requirements, at the same time keeping the nature of the interface features as simple as possible. The eventual interface between vehicle and engines required changes, however, and this aspect of the F-1 resulted in redesign to eliminate problems unintentionally built into the original model.²⁵

The original Air Force prospectus in 1955 called for an engine with a capability of 4 450 000 newtons (1 000 000 pounds) of thrust or more. Various studies went into comparisons of single engines and clustered engines in terms of their availability and reliability. Parallel studies included detailed consideration of engine subsystems to operate at thrust levels of 4 450 000 newtons (1 000 000 pounds) and up. By 1957, Rocketdyne had produced full, detailed analyses of a 4 500 000-newton (1 000 000-pound) thrust engine, and had also produced some models of components for the big engine, as well as a full-scale thrust chamber. In fact, work progressed so well that Rocketdyne began the first attempts to demonstrate main-stage ignition during the same year. The company's work on the F-1 received a big boost from a new Air Force contract awarded in mid-1958. This document called for Rocketdyne to proceed with the design of a 4 500 000-newton (1 000 000-pound) thrust engine, paralleled by the development of appropriate new fabrication techniques, and capped by running initial tests for a thrust chamber and injector components. Including the prior effort, Rocketdyne had attempted several firing tests of the full-sized thrust chamber between 1957 and 1958. In January 1959, Rocketdyne's NASA contract included requirements for a series of feasibility firings of the new F-1 booster; two months later the engine hinted at its future success with a brief main-stage ignition. The trial run demonstrated stable combustion for 200 milliseconds and achieved a thrust level of 4 500 000 newtons (1 000 000 pounds). In conducting these tests, Rocketdyne used a solid-wall "boiler-plate" thrust chamber and injector—a far cry from flight hardware—but the unheard of mark of 4 500 000 newtons (1 000 000 pounds) of thrust had been reached by a single engine.²⁶

Engineers quickly sketched out the dimensions and general configuration of the big new propulsion system, drawing on their prior experience under the aegis of the Air Force and the results of the early "hot" test of preliminary components. At Edwards Air Force Base, where much of the early F-1 research had been accomplished, Rocketdyne unveiled the first full-scale F-1 mock-up on Armed Forces Day, 1960. Edwards continued as the center for full-scale engine testing. Basic research, development, and manufacturing took place at Rocketdyne facilities in Canoga Park, California, and many component tests were conducted at the company's

CONVENTIONAL CRYOGENICS: H-1 AND F-1

Santa Susana Field Laboratory in the mountains nearby. The company lost little time in getting started on real engine hardware. Full-scale tests on the engine's gas generator began in March 1960, and testing of the prototype turbopump got under way in November of the same year. Given the size and cost of the F-1 program, component testing represented an important practice—a technique that Rocketdyne continued to refine during the development phase of the total propulsion system. This "piecemeal" approach avoided the costs and complexities, as well as months of delay, that would have resulted from using the total engine system for the initial tests. Company personnel also conducted "component extended limits" testing, which called for the hardware under test to be pushed beyond its normal performance specifications to establish comprehensive guidelines of reliability and confidence. This concept proved to be so successful that Rocketdyne applied the same extended limits test concept to other engine test programs in progress.

The ability to put components like the gas generator and turbopump through test runs so quickly brought compliments from NASA's engine program managers at MSFC, who appreciated the problems connected with testing such an oversized propulsion system. Rocketdyne personnel pulled off another coup; they not only conducted tests on many full-scale components within a year of the initial contract, but on 6 April 1961, only 27 months from start, they went through a test run of a full-sized thrust chamber assembly prototype at Edwards Air Force Base. During the run, the thrust of the prototype chamber peaked at 7 295 000 newtons (1 640 000 pounds) of thrust—an unprecedented achievement for liquid-propellant rocket engines. Even with the advantages of the Air Force research effort, this was a noteworthy record of accomplishment.²⁷ But a good many predicaments—and sophisticated test work—were to come.

A BIG ENGINE: BIG PROBLEMS

The story of the F-1 development embodied an apparent contradiction: an awesome advance in engine performance and thrust, but an advance based on conventional rocket propellants (liquid oxygen and RP-1) and the existing state of the art. Designers and engineers, whether at government installations or at contractor plants, always had to remember the official NASA admonition about the F-1: keep within the framework of past experience concerning the liquid-fueled rocket engines. Joseph P. McNamara, a top executive at North American and early general manager at Rocketdyne, remarked that the F-1 was really "a big dumb engine" when compared to some of its contemporaries that burned exotic fuels and featured more sophisticated features. Still, it was big. Despite its thoroughly conventional lineage, it was still a major step forward in rocket engine technology. "The giant stride in thrust was to be

STAGES TO SATURN

the major design advancement," said William Brennan, a top Rocketdyne executive. The very size of the engines portended some challenges. MSFC conceded that making "an enlargement of this magnitude is in itself an innovation."²⁸

The scale of the engine always seemed to threaten the goal of keeping the system "old-fashioned" rather than creating a daring new concept. For example, NASA continually emphasized engine reliability because of its intended use for manned missions. In this context, NASA limited the options for fuel and oxidizers for the F-1 to proven types—liquid oxygen and RP-1—and stressed the greatest simplicity in overall engine design. This approach in turn dictated the incorporation of proven component designs wherever possible, combined with advanced metallurgy for added reliability. Once designers got into advanced metallurgy, they got into innovation. Coupled with the factors of size and operating requirements of the F-1, there ensued a number of technological advances and innovations in fabrication techniques.

Despite the accelerating tempo of technological advances in other rocket engines during the development of the maturing F-1, its teething troubles multiplied. Several factors affected early schedules. In the first place, testing programs for the oversized F-1 required new facilities, which had to be constructed. Test equipment had to be compatible with the king-sized proportions of the F-1 test complexes. The design and fabrication of the test equipment alone, in the judgment of MSFC, constituted a "major development." Second, the size of the thrust chamber called for a new brazing process for joining the propellant tubes together. Third, the goal to simplify the engine and related systems resulted in considerable new work to rely on the vehicle's own fuel at high pressure to operate the engine control systems. In eliminating the original plans for a separate hydraulic system, some important redesign had to be done. A fourth area of extra effort stemmed from the extraordinary rate of propellant consumption of the engine (which reached three metric tons of fuel and oxidizer per second). The development of components to meet such demands involved very steep hardware costs and necessitated stringent procedures to obtain maximum use of data acquired from each test. Finally, the application of the F-1 in manned flights created additional requirements for reliability and quality control above the limits normally established for unmanned vehicles. So, despite all the effort to rely on proven systems and components, a distinctly different kind of engine development story emerged. As acknowledged by the manager of the MSFC Engine Program Office, "the development of the F-1 engine, while attempting to stay within the state of the art, did, by size alone, require major facilities, test equipment, and other accomplishments which had not been attempted prior to F-1 development."²⁹

CONVENTIONAL CRYOGENICS: H-1 AND F-1

Fabricated as a bell-shaped engine with tubular walls for regenerative cooling, the F-1 had an expansion area ratio of 16 to 1 (with nozzle extension) and a normal thrust of 6 670 000 newtons (1 500 000 pounds). All engines were identical except for the center engine in each Saturn V, which did not gimbal. To accomplish its mission, the F-1 relied on several subsystems, including the thrust chamber assembly (with the injector and other hardware as integral parts), the turbopump, gas generator system, propellant tank pressurization system, control system, flight instrumentation system, and electrical system. Additional paraphernalia, such as the thermal insulation blankets, were finally adopted as part of the overall F-1 engine propulsion system.³⁰

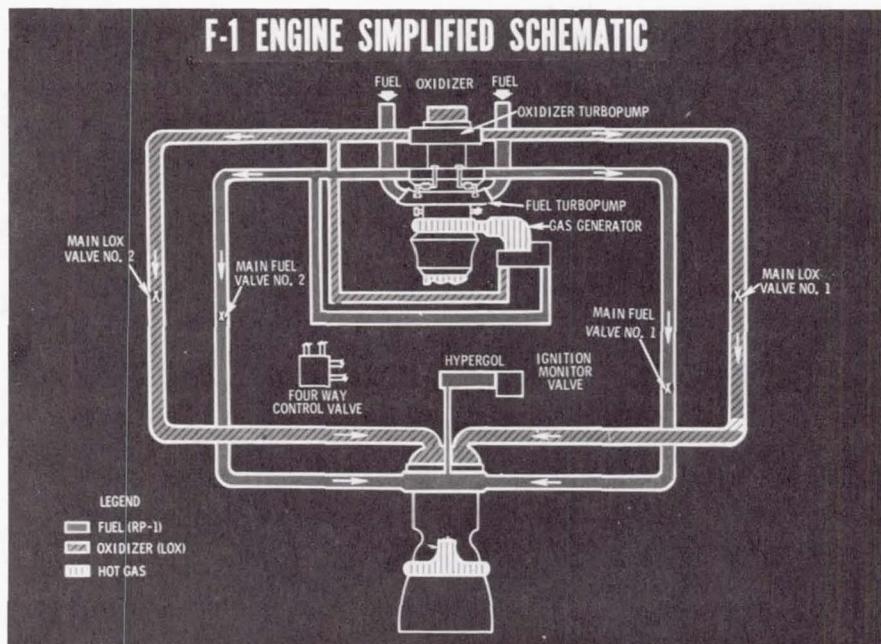
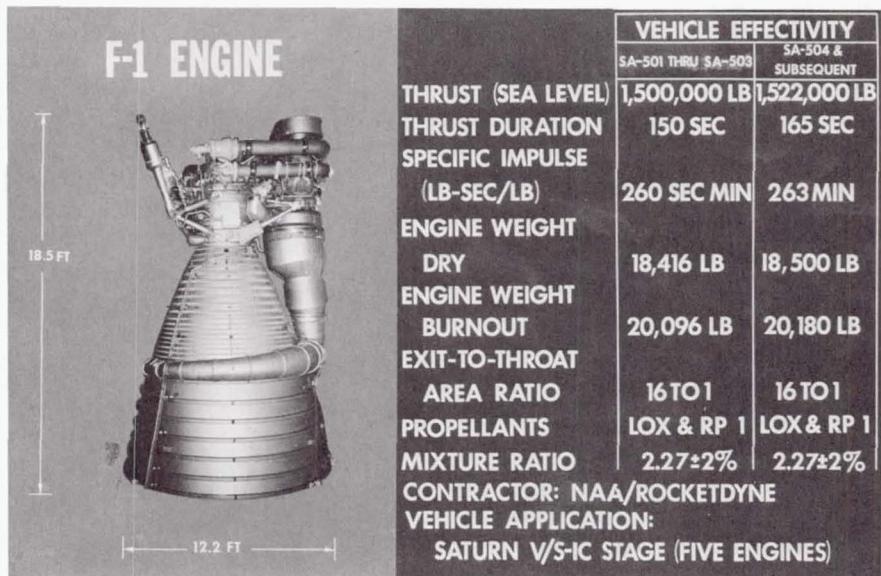
At nearly every step of the way, the unusually large engine exhibited growing pains, and each component required special design attention in one form or another. In some cases, these problems were unanticipated; but even when designers expected a difficult development period, the solutions did not come easily. Such was the case with the F-1 injector.

THE F-1 INJECTOR

The injector sprayed fuel and oxygen into the thrust chamber, introducing it in a pattern calculated to produce the most efficient combustion. To the casual observer, the final production model looked simple enough. The face of the injector, or the combustion side, contained the injection orifice pattern, determined by alternating fuel rings and oxidizer rings, both made from copper. Across the face of the injector, designers installed radial and circumferential copper baffles. These baffles extended downward and divided the injector face into a series of compartments. Along with a separate fuel igniter system, the injector and baffles were housed in a stainless steel body.

In operation, the liquid oxygen dome, or LOX dome, located atop the thrust chamber assembly, channeled oxidizer directly into the injector. Fuel injection followed a somewhat more indirect route, entering the injector from the thrust chamber's fuel inlet manifold. As a means of ensuring the engine start and operating pressure, part of the fuel flowed directly into the thrust chamber, but the remainder was channeled by alternating tubes down the length of the regeneratively cooled thrust chamber, then back up again through the remaining tubes. The fuel entered a fuel collector manifold, consisting of 32 spokes leading to the injector. Finally, the fuel squirted through 3700 orifices into the combustion chamber to mix with the oxidizer, which entered through 2600 other orifices in the injector face.

Obviously, the injector demanded rigorous design work for tolerances and durability under extreme heat and pressures. At Rocketdyne,



David E. Aldrich, the F-1 Project Manager, and Dominick Sanchini, his chief assistant, wasted little time in initiating work on the injector. "Concerning development testing, experience has shown that the injector presents the first major hurdle," Aldrich and Sanchini asserted. "Stable combustion must be attained before injector cooling and other thrust-chamber development problems can be investigated," they explained. At

ENGINE START

- 1 Engine start is part of the terminal countdown sequence. When this point in the countdown is reached, the ignition sequencer controls starting of all five engines.
 - 2 Checkout valve moves to engine return position.
 - 3 Electrical signal fires igniters (4 each engine).
 - a) Gas generator combustor and turbine exhaust igniters burn igniter links to trigger electrical signal to start solenoid of 4-way control valve.
 - b) Igniters burn approximately six seconds.
 - 4 Start solenoid of 4-way control valve directs GSE hydraulic pressure to main lox valves.
 - 5 Main lox valves allow lox to flow to thrust chamber and GSE hydraulic pressure to flow through sequence valve to open gas generator ball valve.
 - 6 Propellants, under tank pressure, flow into gas generator combustor.
 - 7 Propellants are ignited by flame of igniters.
 - 8 Combustion gas passes through turbopump, heat exchanger, exhaust manifold and nozzle extension.
 - 9 Fuel rich turbine combustion gas is ignited by flame from igniters.
 - a) Ignition of this gas prevents backfiring and burping.
 - b) This relatively cool gas (approximately 550°C) is the coolant for the nozzle extension.
 - 10 Combustion gas accelerates the turbopump, causing the pump discharge pressure to increase.
 - 11 As fuel pressure increases to approximately 26,400 grams per square centimeter (375 psig), it ruptures the hypergolic cartridge.
 - 12 The hypergolic fluid and fuel are forced into the thrust chamber where they mix with the lox to cause ignition.
- TRANSITION TO MAINSTAGE
- 13 Ignition causes the combustion zone pressure to increase.
 - 14 As pressure reaches 1 400 grams per square centimeter (20 psig), the ignition monitor valve directs fluid pressure to the main fuel valves.
 - 15 Fluid pressure opens main fuel valves.
 - 16 Fuel enters thrust chamber. As pressure increases the transition to mainstage is accomplished.
 - 17 The thrust OK pressure switch (which senses fuel injection pressure) picks up at approximately 74,500 grams per square centimeter (1060 psi) and provides a THRUST OK signal to the IU.

the outset, it might have seemed logical to scale up designs successfully developed for smaller engines. However, development of a stable injector for the 1 780 000-newton (400 000-pound) thrust E-1 engine required 18 months, and it seemed more than likely that the 4.5-million-newton (1.5-million-pound) F-1 would require something more than just a "bigger and better" design concept.

Rocketdyne's ability to run injector and thrust chamber tests with full-scale hardware in March 1959, only two months from the date of the original contract, derived from its earlier Air Force activities. Some experimental hardware was already on hand, and Rocketdyne also had a usable test stand left over from prior experiments. The first firings were made with components several steps removed from what could be expected as production models. Because the injector paced so much of the overall design and because designers and engineers wanted to start as

STAGES TO SATURN

soon as possible, the thrust chamber tests used rough, heavy-duty hardware; it was cheap, and it was easy to work with.

Investigation began with a critical review of all prior operational injector work and current experimental studies to develop a promising avenue of design for the new component. Advanced theories were needed to understand the operation of an injector at much higher densities and higher chamber pressures than ever attempted. As a result of this preliminary theoretical work, the F-1 injector evolved as a construction of copper rings. This promised the necessary structural rigidity, resistance to localized hot spots, and overheating at the injector face.

With a heavy-duty component in hand, the design work progressed to the next stage of design assessment, featuring a series of water-flow and calibration tests. These procedures verified spacing and shape of injector orifices. The next step involved statistics derived from the flow and calibration tests, giving engineers the kind of data they needed to plan appropriate start sequences for the injector and engine system. The culmination of these investigations occurred in the first hot tests, "one of the most critical stages in an injector development program." These trial runs late in 1960 and early in 1961 marked Rocketdyne's first wave of troubles concerning stability of the injector at rated thrust level for duration firing.³¹

THE INJECTOR AND COMBUSTION INSTABILITY

At the outset, planners considered three different injector designs, all of them more or less based on the H-1 injector configuration. "However, stability characteristics were notably poorer," reported Leonard Bostwick, the F-1 engine manager at MSFC. "None of the F-1 injectors exhibited dynamic stability." Once instability got started in the engine, nothing stopped it until the test engineers cut off the propellants and shut down the entire engine. Obviously, this was not the way to successful missions. The design team tried variations of baffled injectors and flat-faced injectors with little improvement, except that the flat-faced designs could be expected to create more damage than their counterparts with baffles. Finally, all hands agreed that the attempt to scale up the H-1 injector to the F-1 size just would not work. There were too many variables: high chamber pressures, a lower contraction ratio, greater density requirements for the injector, and much larger diameter of the thrust chamber. With the concurrence of MSFC, Rocketdyne began a new path of investigation to select an injector design with inherently stable combustion characteristics.³²

The snags in the F-1's progress sharpened high-level skepticism about the feasibility of an engine the F-1's size. During a meeting of the

CONVENTIONAL CRYOGENICS: H-1 AND F-1

President's Science Advisory Committee early in 1961, one member, Donald Hornig, reportedly expressed strong reservations about the F-1 engine program because of fundamental problems in its development, adding that it might just be too big to make it work. Hugh Dryden, NASA's Deputy Administrator, got wind of these comments and wrote to Hugh Odishaw, of the National Academy of Sciences, to help set the record straight in the scientific advisory community. Dryden reported encouraging progress on new injector designs and characterized the tribulations of the F-1 as inevitable in engine work. "Such development problems are the common experience of every engine development with which I am familiar and are nothing to be concerned about," he counseled, "so long as one makes sure that the developing agency is taking a multipronged approach to obtaining a solution."³³ Several new radial injector designs now became candidates for the F-1 engine. To acquire more accurate data, engineers ran tests with scaled-down models in a special low-pressure, two-dimensional transparent thrust chamber. This permitted the use of high-speed photography and "streak movies" to analyze the performance of the injectors in simulated operation. The most promising designs graduated to full-sized models in hot-fire tests which included bomb experiments (as in the H-1) and erratic propellant flows produced by an explosively driven piston. The new designs appeared to have combustion instability, an early concern, under control until 28 June 1962, when combustion instability resulted in the total loss of an F-1 engine. From there on, as von Braun drily remarked, "This problem assumed new proportions."³⁴

Working quickly, MSFC established a combustion stability ad hoc committee, chaired by Jerry Thomson of Marshall, with six permanent members and five consultants chosen from MSFC, Lewis Research Center, the Air Force, industry, and universities. The group got together at Huntsville on 16 July to consider the recent loss of the F-1 engine and to review Rocketdyne's R&D efforts, as well as to provide technical assistance and coordinate all research on the problem. Rocketdyne had established its own stability council by the autumn of 1962 to pursue the issue of F-1 instability and also enlisted the support of leading authorities from government and universities. Rocketdyne's group was headed by Paul Castenholz and Dan Klute, temporarily relieved of their current duties for full-time attention to combustion instability. They reported directly to William J. Brennan, Rocketdyne's chief of propulsion engineering at the time.³⁵

Reacting to deep concern expressed within the Office of Manned Space Flight, von Braun prepared a memo in November 1962 to reassure Seamans and others at Headquarters. Von Braun emphasized Marshall's concern and praised the steps taken by Rocketdyne to deal with the situation, but promised no quick or easy solutions. The memo from von

STAGES TO SATURN

Braun gave a clear insight into the frustrations in searching for answers. Although various organizations had pursued combustion-instability research for the past 10 years, nobody had yet come up with an adequate understanding of the process itself. Therefore, it had not been possible to use suitable criteria in designing injectors to avoid combustion instability. "Lack of suitable design criteria has forced the industry to adopt almost a completely empirical approach to injector and combustor development," von Braun said. This approach is not only "costly and time consuming," he continued, but also ". . . does not add to our understanding because a solution suitable for one engine system is usually not applicable to another." Von Braun urged more extensive research on the task, and suggested that universities in particular could put Ph.D. candidates to work on aspects of combustion and combustion instability for their dissertations.³⁶

In the meantime, two more engines were lost in tests. D. Brainerd Holmes wanted a special briefing on the problem, which he received on 31 January 1963. At the end of the presentation, Holmes commented that the goal of beating the Russians to the moon seemed to mired in F-1 problems. He asked if it was not time to start work on a backup scheme. The briefing team, which included representatives from MSFC and Rocketdyne, convinced Holmes that new work would detract from solving F-1 difficulties, which appeared to be succumbing to intensive government-industry engineering and university research.³⁷ In March, however, Holmes wrote to von Braun, reemphasizing the need to get the F-1 effort on schedule to avoid slips in launch dates and the lunar landing goal. "I regard this problem as one of great seriousness," Holmes wrote, and asked to be kept informed on a daily basis.³⁸

It took 12 months for Rocketdyne to work out a baffled injector design that functioned well enough to pass the preflight rating tests. Some vexatious anomalies persisted, however, especially in the injector's inability to recover from combustion oscillations artificially induced by bombs detonated inside the thrust chamber. This situation called for added research before the F-1 could pass muster for the final flight-rated design. By July 1964, with combustion stability work continuing, Rocketdyne received an additional contract of \$22 million, including miscellaneous hardware and services, with a special allocation to accelerate the company's research in combustion stability.³⁹

Significant theoretical work was accomplished by two Princeton researchers, David Harrje and Luigi Crocco, along with Richard Priem of the Lewis Research Center. When Crocco was in Europe on sabbatical during the academic year 1963–1964, he maintained correspondence with MSFC; NASA Headquarters even approved von Braun's request to send Rocketdyne and Marshall representatives to talk with Crocco in

CONVENTIONAL CRYOGENICS: H-1 AND F-1

Rome.⁴⁰ To investigate the phenomenon of unstable combustion, engineers and researchers employed a wide range of instrumented apparatus and other aids. Among other paraphernalia, investigators introduced high-speed instrumentation to diagnose combustion in the thrust chamber and to evaluate modifications to the original designs. The exacting attention to details led to apparently minor changes that actually proved to be of major significance. After careful calculations of the effect, enlarging the diameters of the fuel injection orifices was later judged one of the most important single contributions to improved stability. Other careful changes included readjustment of the angles at which the fuel and oxidizer impinged.⁴¹ Several techniques of rather dramatic nature were also applied in the instability research. For the layman, the most bizarre aspect of F-1 testing (like the H-1) involved the use of small bombs to upset the thrust exhaust pattern to measure the engine's ability to recover from the disturbance. By varying the size of the bombs, test engineers could create instability of different intensities and evaluate the ability of the engine to restore stable conditions.

This procedure offered an immense saving in time and costs, because it eliminated the old methods of running hundreds of engine tests in an effort to acquire a quantity of useful statistics. Moreover, the ability to artificially subject the F-1 injector to severe operational stresses eventually resulted in a superior design with excellent damping characteristics. During early tests, self-triggered instability continued for more than 1600 milliseconds—a highly dangerous condition. The successful design recovered from deliberately triggered instability in less than 100 milliseconds. The final product included the redesigned orifices for LOX and fuel to improve the distribution pattern of propellants as well as a rearrangement of the injector baffles. The baffled injector, as opposed to the flat-faced type, was particularly effective in recovery during the deliberately triggered instability tests. The minute, exacting requirements of engine development were such that these seemingly insignificant changes required some 18 months to prove out, and the flight-rated model of the F-1 injector did not receive MSFC's imprimatur until January 1965.⁴²

In the course of F-1 engine development, Rocketdyne personnel consistently emphasized the combustion stability investigations as one of the company's stiffest challenges, and its solution as one of its most satisfying achievements. Although engineers expected difficulties in this area because big engines with high chamber pressures inevitably developed random and unpredictable combustion instability, the size of the F-1 dramatically increased the size of the challenge. Rocketdyne managed to cope with the problem, although, as Brennan admitted in an address to the American Institute of Aeronautics and Astronautics in 1967, "the

STAGES TO SATURN

causes of such instability are still not completely understood.⁴³ Even though the F-1 engine performed satisfactorily, uncertainty concerning combustion instability persisted a decade later.*

Although combustion instability and injector development became the pacing items in the F-1 program, other thrust chamber problem areas required constant troubleshooting by Marshall and Rocketdyne engineers. During the first half of 1965, MSFC monitors at Rocketdyne's production facilities in Canoga Park, California, were worried about cracks in the thrust chamber jacket, while MSFC monitors at the Edwards Air Force Base test site were frustrated by cracks in the thrust chamber tubes. Engine 014 had been in and out of the test stand more than once for injector changes and thrust chamber tube repairs. In April 1965, the MSFC monitor at Edwards reported to Huntsville that the engine was back in the test stand once more. "Engine 014 apparently has a dog of a thrust chamber," he wrote in exasperation.⁴⁴ Another troubleshooting effort that required considerable attention concerned a manufacturing sequence for the injectors. Unhappily, the problem appeared after a number of engine deliveries to the Boeing Company, the contractor for the S-IC first stage of the Saturn V. The injector incorporated multiorificed copper fuel and oxidizer rings, held by steel lands (rings) installed in a stainless steel body. To attach the copper rings to the steel lands of the injector body, workers performed a brazing operation. As test runs on R&D engines accumulated more and more time, the brazed bond joint failed, with very bad separation between the copper rings and steel lands. Analysis of all prior engine deliveries disclosed similar minute failures. In a somewhat elegant solution, new procedures called for replacements using gold-plated lands to offer a superior bonding surface during brazing. During the spring and summer of 1965, this investigation involved considerable testing and metallurgical analysis, not only to pinpoint the problem, but to confirm the effectiveness of the new procedures. Finally, several engines had to be retrofitted with the new "gold-plated" injectors.⁴⁵

THE F-1 TURBOPUMP

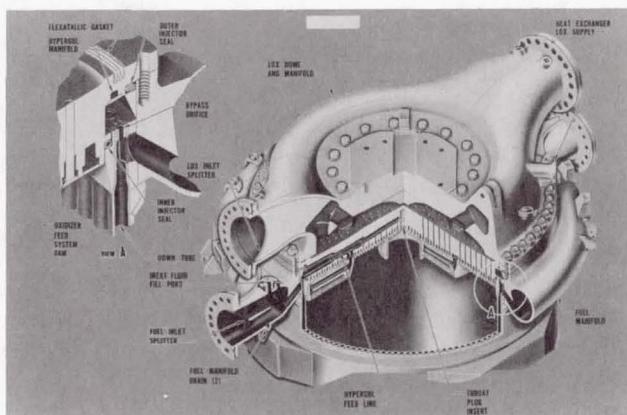
As one group of specialists grappled with injector or thrust chamber problems, another group labored on the problem of pumping hundreds of thousands of liters of propellants out of the S-IC's propellant tanks and into the five F-1 engines. The turbopump absorbed more design effort and time for fabrication than any other component of the engine.

* In a note to the author (8 July 1976), John Sloop, a senior NASA propulsion engineer, noted that combustion instability, like engine knock, has long been studied, and engineers had learned to deal with it. But neither was yet fully comprehended.

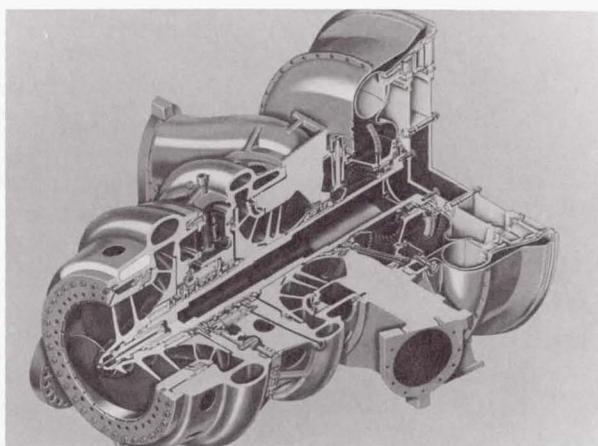
CONVENTIONAL CRYOGENICS: H-1 AND F-1

The development program began with tests of various models of turbopump evaluating the performance levels and durability of fuel and oxidizer pumps, inducers, and turbines. With a satisfactory preliminary design worked out from the model testing, workers assembled a full-sized turbopump and started tests in November 1960.⁴⁶

Rocketdyne designed the turbopump as a direct-drive unit, with the oxidizer pump, fuel pump, and turbine mounted on a common shaft. During operation, the engine bearings were cooled by fuel, but this



Above, a cutaway drawing of the liquid oxygen dome and the injector plate of the F-1 engine; below, a cutaway drawing of the Mark 10 turbopump for the F-1 engine.



STAGES TO SATURN

convenient feature required a special heater to keep the ball bearings from freezing up when the pump was chilled by liquid oxygen prior to engine start. The oxidizer pump, rated at 102 230 liters (24 811 gallons) per minute, supplied oxidizer to the thrust chamber as well as to the gas generator. Oxygen entered the pump through an inlet connected to the oxidizer tank by a duct, and the inlet had an inducer mounted in it to increase the pressure of the oxidizer before it reached an impeller. This sequence prevented cavitation in the liquid oxygen stream. The impeller brought the oxygen to the correct pressure, then discharged it through appropriate routes to the thrust chamber and gas generator. With a rated capacity of 57 392 liters (15 741 gallons) per minute, the fuel pump supplied the thrust chamber and gas generator in the same manner as the oxidizer pump. The fuel pump system also employed an inducer section to prevent cavitation before the fuel reached the impeller.

The turbine to drive the separate propellant pumps was an impressive piece of machinery itself—it developed 410 000 watts (55 000 brake horsepower). Designers located the turbine on the fuel-pump end of the turbopump. In this position, the units of the turbopump with the most extreme temperature differences (816°C [1500°F] for the turbine and -184°C [-300°F] for the oxidizer pump) were separated. Hot gases for the turbopump turbine originated in the gas generator and entered the turbine at 77 kilograms per second.⁴⁷ A series of failures, 11 in all, dogged the development of the turbopumps for the F-1 engine. Two incidents were traced to structural failures of the LOX pump impeller, which called for redesign of the unit with increased strength. Explosions occurred in the other nine instances, with five during engine tests and four during component tests of the turbopump. The explosions developed from a variety of causes, such as shock loads due to high acceleration of the turbopump shaft, rubbing between critical seals and other moving parts, fatigue in the impeller section, and other problems. With some new design work and manufacturing techniques, these conditions disappeared, and investigators proceeded to cope with other problems that continued to crop up, such as the engine turbine. For the engine turbine manifold, Rocketdyne chose a new material known as René 41. This material was quite new to the manufacturers of rocket engines, and the welding process produced cracks adjacent to the weld in the heat-affected zone created by the welding pass. As a result, the company devoted considerable time and effort to ascertaining proper welding conditions and to training welders on the production lines. With the proper welding requirements finally established, Rocketdyne adopted an automatic welding procedure to complete the "fix" on this situation.⁴⁸

The turbopump was a good example of the emphasis on simplicity and reliability in design philosophy. "The primary consideration in the selection of the turbopump design," MSFC managers emphasized, "was to attain reliability by using a minimum number of parts and proven

CONVENTIONAL CRYOGENICS: H-1 AND F-1

design concepts." Engineers were anxious to have a turbopump capable of operating at low inlet pressures, both to simplify design requirements and to have low pressure in the propellant tankage. The packaging concept of the F-1 influenced the design of the turbopump system. The main objectives in the engine configuration included designing components to be as small as possible and keeping machinery as accessible as possible. In general, the configuration of the engine package followed the pattern of the Atlas sustainer engine (the S-4), Rocketdyne's first large liquid-propellant gimbaled engine with the turbopump mounted directly on the thrust chamber. Designers located all other associated equipment on the turbopump, thrust chamber, or somewhere in between. The attraction of this approach, as in the H-1, lay in the ability to avoid flexing the high-pressure propellant ducts in concert with the gimbaling engines during a launch.

The F-1 turbopump assembly featured a variety of manufacturing techniques, heat treatment, and other processes to impart the most desirable properties to the high-performance engines. A good example of evolutionary steps in the process of engine development, these aspects of the F-1 fabrication grew out of the special materials programs associated with the H-1 engine. In both cases, designers selected materials intended to provide extra margins of safety whenever possible. For the pump's inlets, volutes, and impellers, the F-1 incorporated a light-weight, but sturdy, aluminum-alloy casting. For turbine wheels and manifold assemblies that performed under higher operating temperatures, designers favored a nickel alloy with high strength at high temperatures. After running hundreds of tests on final designs of the F-1 turbopump assembly, its developers were at last satisfied with the performance of the materials chosen and the design philosophies that were used.⁴⁹

THE F-1 THRUST CHAMBER AND FURNACE BRAZING

At a rate of three metric tons per second (one metric ton of RP-1 fuel and two metric tons of liquid oxygen), the F-1 was designed to burn its propellants at approximately 79 000 newtons per square centimeter (1150 pounds per square inch) at the injector face (the high pressure was emphasized as a matter of efficient design), and within the thrust chamber convert this furious activity into a high-temperature, high-velocity gas with a yield of 4.5 million newtons (1.5 million pounds) of thrust.

Before entering the thrust chamber body tubes, RP-1 entered the fuel manifold from two diametrically opposed inlets. The bypass (which channeled about 30 percent of the fuel flow directly to the injector) reduced the power requirement for the fuel pumps—they did not have to force all the fuel down the cooling tubes and up again to the

STAGES TO SATURN

combustion chamber. The remainder of the RP-1 was diverted down through 89 tubes to the nozzle exit, where a return manifold directed fuel back through the 89 return tubes. In the lower sections, the tubes were actually bifurcated units. From the fuel mainfold down to the point where the engine attained a 3.1 expansion ratio, the tubes were installed as single pieces. Below that point, the manufacturing process included two secondary fuel tubes, each spliced into the primary carrier. Designers went to this configuration to compensate for the increasing flare of the bell-shaped nozzle. The bifurcated units in the flaring nozzle permitted the engine to retain a desirable cross-sectional area in each tube and still achieve the wide, flared bell shape.⁵⁰

Transforming the thrust chamber's individual tubes into a vessel capable of handling the F-1 pressure and heat required specialized metallurgical research in Rocketdyne laboratories and at MSFC. To form the regeneratively cooled engine, the F-1 was fabricated as "a tube bundle surrounded by a heavily jacketed combustion chamber, a series of bands around the nozzle, and two end rings." The basic thrust chamber included 178 primary tubes and 356 secondaries, requiring 900 meters of brazed joints between them to keep the combustion gases contained within the thrust chamber. Rocketdyne personnel expended a great deal of effort on the perfection of brazing operations required for the nickel-alloy thrust chamber assembly; it was a major challenge to perfect an alloy and a brazing technique to seal the hundreds of tubes together in a bond that would withstand high temperatures and pressures. The joints carried some of the stresses created by the expanding combustion gases, but the jacket and reinforcement bands around the tube bundle carried the primary load. This basic F-1 design reflected the features of other regeneratively cooled engines with tubular walls, such as the Atlas and H-1 engines. The greatly increased operational factors of the F-1 required more sophisticated fabrication methods, which led the company, finally, into the design and construction of the largest brazing furnace of its type in the world.

In the production of less powerful liquid-rocket tubular-walled thrust chambers, usually of pure nickel, manufacturing engineers depended on manual torch brazing with alloys of a silver-based type. With the F-1's thrust levels up to 10 times those of prior engines, investigators knew that the old procedures needed some rethinking if the big new engine was going to hold together during a launch. For the tubes themselves, the nickel-alloy Inconel X-750 provided the high strength-to-weight ratio that was needed, but it imposed certain restraints in the brazing process. After experimentation, designers realized that technical reasons prohibited the conventional technique of torch brazing, and dictated a furnace brazing process. Then a secondary set of problems cropped up. Inconel X-750 included enough aluminum and titanium to form refractory oxides under brazing temperatures, so that "the surface of the Inconel is

CONVENTIONAL CRYOGENICS: H-1 AND F-1

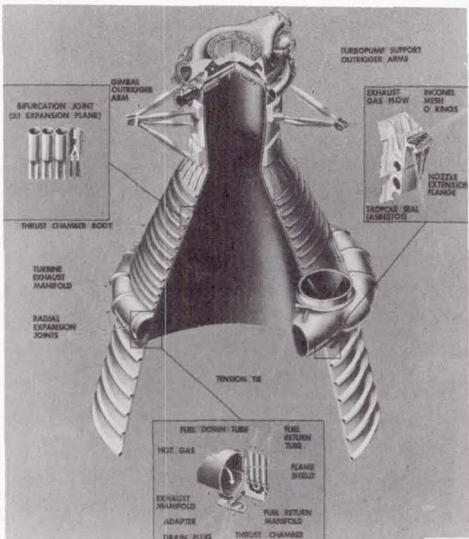
not readily wet by most brazing alloys at elevated temperatures." Thus the brazing procedures had to begin by electrolytically depositing a thin layer of pure nickel on the tubes to eliminate the refractory oxides on the brazing surface. Despite this minor drawback in the operation, furnace brazing promised several distinct advantages over the torch method by minimizing differences in thermal stresses, combining age-hardening of the tubes with the brazing operation, and eliminating the variables of hand methods.⁵¹

With the furnace activated in 1965, furnace brazing for F-1 production proceeded in several carefully regulated sequences. After preliminary brazing operations to unite the thrust chamber tubes and other components, the scene was set for the final furnace brazing cycles to create a properly sealed thrust chamber. Inside a "clean-room" area, workers assembled the complete thrust chamber, using a special fixture devised by Rocketdyne to ensure proper alignment of the tube bundle, jacket, and end rings. In addition to the 900 meters of tube-to-tube alloy joints to be sealed inside and outside, the exterior required some 7000 tube-to-band joints to be brazed. The brazing alloy, in a powder form, was applied by workers using hand-held spray guns, an application technique also especially developed by Rocketdyne.

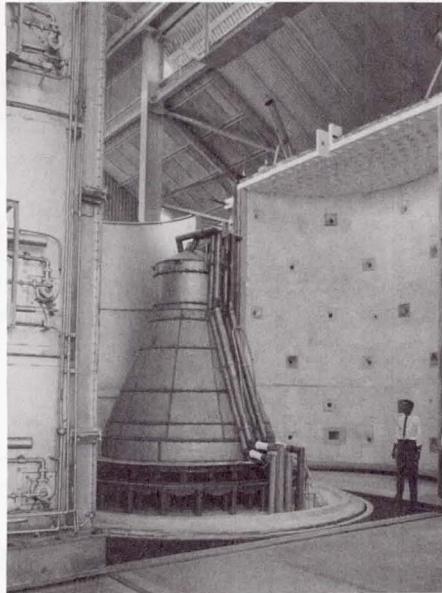
Despite the highly refined and closely monitored steps leading up to the first major furnace brazing operation, this operation remained heavily laden with drama since it could almost as easily go sour as succeed. As one Rocketdyne engineer emphasized, "The furnace brazing operation represents a final step in which all the material, time, and resources expended in the fabrication of hundreds of thrust chamber parts and subassemblies are committed. In many respects it is similar to the launch of the vehicle itself, since failure of any one of the numerous controls exercised during the furnace brazing operation could result in a poorly brazed, unacceptable piece of hardware." No wonder, then, that Rocketdyne expended so much attention on the furnace, which incorporated several unique features of design and performance.⁵²

OTHER COMPONENTS AND SUBSYSTEMS

The F-1 design included a thrust chamber extension, or "nozzle skirt." As engineers pondered the design of the F-1 and the problem of disposing of the turbine exhaust, the idea of the nozzle skirt promised several design advantages. A circumferential exhaust manifold collected the turbine exhaust gases and directed them through the nozzle skirt into the engine's exhaust plume. The skirt was designed with double walls, and numerous slots in the wall allowed the gases to exit with the jet stream of the exhaust. The effect was to introduce a cooler boundary layer to protect the walls of the thrust chamber extension. With the



Above, a cutaway drawing of the F-1 thrust chamber; right, the huge furnace at Rocketdyne in which the tricky brazing operation was performed on F-1 engine thrust chambers at 1260°C.



disposal of the turbine exhaust gases into the thrust chamber by way of the nozzle extension, Rocketdyne designers realized the advantages of a neat, comparatively lightweight system. There was no need for extra attachments such as a turbine exhaust duct, and the extension favorably increased the expansion ratio. Designed with simple bolted attachments, the extension could be conveniently removed for shipping and handling of engines and stage. The simplicity of the design allowed the engine to be easily test-fired following reattachment of the nozzle skirt at the test site.

To help keep the S-IC propellant tanks under pressure, the engine contractor supplied elements of the propellant tank pressurization system. The key to the system was the heat exchanger, which heated gaseous oxygen and helium to pressurize the oxidizer tank and fuel tank, respectively. Using the vehicle's own oxidizer as part of the propellant tank pressurization system illustrated harmoniously integrated design of many of the rocket systems and subsystems. Another good example involved the use of the fuel as the fluid medium in the hydraulic control system. The hydraulic design itself constituted a notable design advancement for an engine the size of the F-1. The system cut out many sets of

CONVENTIONAL CRYOGENICS: H-1 AND F-1

previously required pneumatic controls and electrical components and automatically increased reliability. Once the fuel used as the hydraulic fluid had performed its programmed chores in engine components, a myriad of tubing routed it back to the turbopump fuel inlet for combustion in the thrust chamber.

The frustrations of perfecting an engine the size of the F-1 ran the gamut from internal hardware to external accessories. The high operating temperatures of the engine called for varied insulation at many points, and the super-hot blasts from the clustered engines created the need for special insulation to protect the engines from their own exhaust. During the vehicle's ascent, the plumes from the five F-1 engines expanded with decreasing ambient pressure until they became one searing, gargantuan sheet of flame, and a backlash stream of hot gases played over all the exterior surfaces of the engines. For this reason, designers had to protect the engines from thermal attack during the flight, as well as consider the high heat radiation encountered as the engines built up to mainstage thrust levels at liftoff. Thus, the F-1 engine acquired its distinctive external insulation "cocoon," molded into segments and attached to the engine with brackets. Despite its deceptively simple appearance, the development of this insulation cocoon also experienced its share of problems in attachment and weight.

Engineers employed a direct and brutal method to test the engine insulation cocoon installed on the F-1. Workers placed an engine, enclosed in its protective wraps, inside a special wind tunnel. At one end, they installed a J-57 jet engine, complete with an afterburner, and positioned it to aim the devastating jet exhaust directly at the insulated F-1. With added quilting, thicker inner skin, and improvements in stressed areas, the engine insulation received qualification for flight. Only one more hitch occurred. In the humid, semitropical environment of Cape Kennedy, the internal quilting acted like a sponge and became thoroughly saturated during a stiff thundershower. While a Saturn V waited on the pad, engineers ran frantic tests with water-soaked insulation panels under simulated flight conditions. These tests introduced the final modifications to the insulated cocoons—strategically placed vents to let off steam from the moisture-laden internal quilting.⁵³

FROM STATIC TEST THROUGH FLIGHT TEST

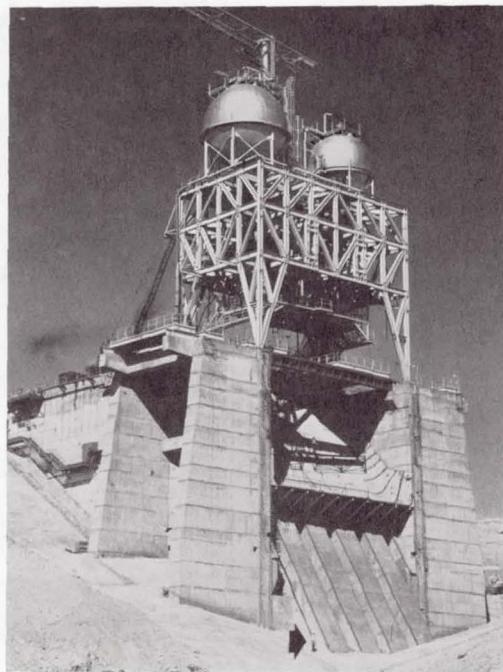
From the beginning, the most complete facilities for full-scale F-1 testing existed at Edwards Air Force Base, where Air Force work on the engine first began. Their facilities included several engine test stands and a thrust chamber stand, also used for injector design studies. The first engine tests using prototype hardware occurred in the test stand originally built for the Atlas program and converted to take the larger F-1

STAGES TO SATURN

dimensions. Researchers scheduled advanced engine work to use a new stand, capable of holding a pair of engines side by side. It was a towering complex, equivalent to an 11-story building, built with heavily reinforced concrete base and a steel girder framework anchored deeply in the desert granite to withstand the punishment of the F-1 engines at full throttle. At the peak of the development program, Rocketdyne used five separate engine stands at the Rocket Engine Test Site, an integral unit of the Edwards Air Force Base complex. The equipment at the Edwards Rocket Engine Test Site also included a component test stand, a dual-position facility used for chamber and injector work at full thrust levels. Technicians began some of the first preliminary design work on this stand, even though it was not feasible at the time to build supply tanks to deliver propellants for more than a 20-second run. Despite the short duration of the experiments, the 20 seconds of roaring engine operation called for some equipment of remarkable proportions. Workmen put together the high-pressure propellant tanks with stainless steel plates 13 centimeters thick and installed fuel and oxidizer control valves that weighed 6 metric tons each. With such a complement of metal, the "battleship test" stand was aptly named.⁵⁴

To accelerate the test schedules for production models of the F-1, executives at MSFC decided to test the engines in Huntsville and ordered appropriate modifications to the west side of MSFC's static test tower. Thus, while the engine test stands at Edwards supported ongoing research and development, Marshall personnel checked out the first batch of production engines during 1963, sending the F-1's thundering roar through the Tennessee River valley. The tempo of F-1 engine tests picked up during 1964, as MSFC personnel ran numerous static tests in Huntsville, and Rocketdyne supervised continuing work at Edwards Air Force Base. In October, the new dual-position test stand at Edwards became operational. The Director of MSFC, Wernher von Braun, flew out to California for the ceremonies, where he accepted the newly activated stand on behalf of NASA and then assigned operational responsibility to Rocketdyne. With all test stands utilized at full capacity, the Flight Rating Tests of the F-1 propulsion system soon concluded, and flight qualification was verified by NASA spokesman by the last month of the year. The concurrent lines of development of stages and engines now began to converge in Huntsville where a "live" test stage (the S-IC-T), with a full complement of five F-1 engines, awaited its first dramatic test firing. The use of MSFC facilities on 16 April 1965 put this phase of testing two months ahead of schedule, and the 6.5-second ignition of the S-IC-T stage generated 33 000 000 newtons (7 500 000 pounds) of thrust, more collective rocket power than ever before achieved.

During 1966, the last year before the F-1 and J-2 powered Saturn V was scheduled for its first unmanned launch, the F-1 passed NASA's first article configuration inspection, the first major Apollo-Saturn propulsion



The F-1 test stand in the Mohave Desert towered 76 meters (note man at base).

system to pass this exam, and on 6 September the F-1 received complete qualification for manned missions. The final tests for MSFC occurred on 15 November, with the acceptance firing of the S-IC-3 first stage; subsequent acceptance firings were earmarked for the Mississippi Test Facility near the Gulf, a more convenient location in terms of logistics between the test site and launch facilities at KSC. Before the epochal voyage of Apollo 11 began on 16 July 1969, five Saturn V launch vehicles lifted off from Cape Kennedy: one in 1967; two in 1968; and two more in early 1969. Despite the thousands of metric tons of cryogenic materials already consumed in research and in the hundreds upon hundreds of tests already accomplished, the pace of research involving the F-1 only seemed to quicken in the concluding months before Apollo 11 began its flight. Dozens of additional tests of the complete engine were run at Huntsville and at Edwards, as contractors and NASA engineers determinedly verified the maturity and reliability of the mammoth rocket engine.⁵⁵

SUMMARY: H-1 AND F-1

The H-1 and F-1 engines, as well as other engines in the Saturn series of vehicles, achieved remarkable records in operational reliability and longevity during the Apollo program. Both the H-1 and F-1 demonstrated consistent performance characteristics during flight missions, a credit to all the government and contractor personnel who



The production line for F-1 engine thrust chambers at Rocketdyne.

contributed to their success. When the Saturn V took the central role in the late 1960s and early 1970s, the remaining nine Saturn S-IB first stages, along with their 72 H-1 engines, went into storage. When they were earmarked for use in the Skylab program, many people wondered if such old equipment would still be reliable.

In the spring of 1971, nine years after the delivery of the last production unit, technicians pulled one of the H-1 engines out of hibernation, to test the "certified lifetime" of seals, gaskets, and other components. The test was important, not only for the immediate purpose of Skylab, but to know how other liquid-fueled rocket engines stored away for future missions were faring. After an extensive pretest examination, the H-1 was installed in a test stand at MSFC. Engineers put the engine through its paces: three separate starts, followed by a full-duration run of 140 seconds. The engine performed as well as at its qualification test firing, 108 months earlier. MSFC personnel tore the engine down after firing to see if they could discover any weaknesses, but all the seals and other critical parts were still in good shape and fully serviceable. Marshall officials sent the engine back into storage, satisfied that they could all be called upon to serve any time within yet another 8–10 years. A year later, during June 1972, Rocketdyne personnel did similar tests on an F-1 engine that had been delivered to MSFC in 1965, tested in 1966, and put into storage. The engine was run through two extended duration firings at Edwards Air Force Base, then subjected to rigorous inspection and analysis. The engine showed no abnormalities.⁵⁶ Faith in the engines' lifetime was justified by the successful launch of the Orbital

CONVENTIONAL CRYOGENICS: H-1 AND F-1

Workshop aboard a two-stage Saturn V (S-IC first stage and S-II second stage), followed by the three successful manned launches of the Saturn IB in support of the Skylab program in 1973, followed by another Saturn IB in the Apollo-Soyuz Test Project in 1975 (see chapter 13).

To appreciate the efficiency and dependability of the H-1, the contributions of engine technology from the Thor, Jupiter, and Atlas programs must be remembered. These missile propulsion systems contributed handsomely to the H-1 engine's thrust chamber, turbopump assembly, gas generator system, control valves, and other engine assemblies. But the H-1 emerged from its R&D gestation period as a separate and distinct engine system. Its components had been completely repackaged for compactness and improved accessibility—the latter a special problem for the H-1, created by the first-stage "boat tail." Various components were refined and strengthened for higher pressures, temperatures, and propellant flow to achieve the higher thrust levels demanded for the Saturn missions. Altogether, the designers contrived an assembly that was smaller and lighter in comparison to its enhanced performance.⁵⁷

Although the F-1 had its roots in early Air Force studies, it was a "newer" engine than the H-1. Troubles with the F-1, however, were primarily a function of proportions, not innovations. Both engines used the same liquid oxygen and RP-1 propellants, but size and performance characteristics made the F-1 fundamentally different. The H-1 experienced R&D problems as it was uprated in thrust. Taking proven H-1 components, such as the injector, and scaling them up to F-1 requirements turned out to be not only difficult but basically impossible. The job necessitated a fresh approach. Reworking the engine and the injector to cope with combustion instability entailed an R&D effort of notable scope, embracing scientific and technical specialists from MSFC and other NASA centers, the contractor, other government agencies, private industry, and universities. In addition to other F-1 complications, the nature of the facilities for testing and manufacturing (furnace brazing, for example) of the F-1 also differentiated it from the smaller H-1.

The extent to which cryogenic oxidizers and fuels of the RP-1 type had been used in earlier engines made the H-1 and F-1 conventional propulsion systems. Other Saturn cryogenic engines used a different, more potent fuel: liquid hydrogen. As the first large rocket engines to use a cyrogenic fuel, the RL-10 and J-2 were unconventional.

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5

Unconventional Cryogenics: RL-10 and J-2

Liquid hydrogen fuel appealed to rocket designers because of its high specific impulse, a basic measure of rocket performance. Compared to an RP-1 (kerosene) fueled engine of similar size, liquid hydrogen fuel could increase the specific impulse of an engine by 40 percent.¹

Research into, and application of, gaseous hydrogen technology waxed and waned over a period of two centuries. Hydrogen's buoyant qualities when used in balloons made it an early favorite of daring balloonists in the late 18th century, until the latent flammability of hydrogen ended too many balloon flights—and balloonists' careers—in dramatic fashion. Beginning in World War II, development of large dirigibles brought hydrogen into the limelight once again. In the 1920s and 1930s, mammoth airships bearing the flags of the United States, England, France, and Germany challenged the ocean of air. Because the United States withheld helium for strategic reasons, the great German zeppelins had to use hydrogen for buoyancy. With stringent safety precautions, the zeppelins operated with astonishing reliability and safety on intercontinental routes for some years, until the cataclysmic destruction of the *Hindenburg* in 1937 brought another halt in the development of hydrogen for travel. Following World War II, the public associated hydrogen with doomsday weapons, as the Cold War era culminated progressive development of nuclear arms in the hydrogen bomb, or "H-Bomb," of the 1950s. While use of hydrogen was being perfected for destructive purposes, developments in rocketry opened the way for a more benign application in NASA's space program.

Serious consideration of liquid hydrogen as a rocket fuel dated from 1903 when Tsiolkovsky, in his *Treatise on Space Travel*, proposed a rocket

STAGES TO SATURN

engine powered by a combination of liquid oxygen and liquid hydrogen. However, liquid hydrogen could not be obtained in quantities for extensive experimental investigations, and for many years, it remained a laboratory curiosity with a tantalizing potential.² Significant research and development of liquid hydrogen fuel and engines faltered in the United States until the closing months of World War II, when wartime rocket development led to consideration of succeeding generations of rocket engines and fuels.

THE LURE OF LIQUID HYDROGEN

Late in 1945, the Navy Bureau of Aeronautics inaugurated a program to investigate the potential of liquid hydrogen as a rocket propellant. During the following year, the Navy formed the Committee for Evaluating the Feasibility of Space Rocketry (CEFSR), within the naval Bureau of Aeronautics, to review the problems of fuels, engines, vehicle structures, and other ramifications of advanced rockets. Within the year, CEFSR proposed a single-stage rocket, with liquid hydrogen as propellant, to boost a satellite into orbit. It was a very advanced concept, requiring hardware well ahead of the state of the art. Members of the CEFSR dubbed their vehicle the High Altitude Test Vehicle, or HATV. The bureau then negotiated a contract for additional studies with the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. Investigators at JPL confirmed the feasibility of the concept of a satellite booster fueled with liquid hydrogen. Led by Dr. Théodore von Kármán, several JPL engineers, intrigued by the esoteric problems of aerodynamics and space flight, had already organized a small and highly specialized corporation, the Aerojet Engineering Corporation, which seemed ideally suited to tangle with some of the hardware problems associated with the development of liquid hydrogen propellants, engines, and related systems. Under a separate Navy contract, Aerojet took on the responsibility of setting up a plant to produce liquid hydrogen in volume, and developing test stands to try out experimental liquid hydrogen rocket engines.³

The work at Aerojet included the design, construction, and operation of high-performance injectors and thrust chambers that operated in the range from 1780 newtons (400 pounds) of thrust to 13 350 newtons (3000 pounds) of thrust. The company also successfully tested a liquid hydrogen engine pump, a single-stage centrifugal model that performed with shaft speeds up to 35 000 revolutions per minute. In 1947, the Aerojet General Corporation announced a working 13 350-newton (3000-pound) thrust liquid hydrogen engine. The direction of the work, and the attendant requirements for cryogenic supplies and storage, led to the design, construction, and operation of a plant to produce liquid hydrogen by 1949. Investigation of cryogenic engines was also under way

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

at Ohio State University, under the direction of Dr. Herrick L. Johnston, whose research team successfully fired a liquid-hydrogen engine of significant size in 1945. Dr. Johnston served as a consultant in the design of the California plant and contributed several technical devices used in the operational layout. The insulation procedures for this pioneering facility were also adapted from Johnston's research at Ohio State.⁴

The Aerojet operation afforded invaluable experience in the production and handling of liquid hydrogen, which seemed to be less ticklish than hydrogen gas. "On the whole," some early personnel recalled, "liquid hydrogen is less hazardous than high-pressure gaseous oxygen, and it may, in fact, be regarded as a highly volatile gasoline." Much of the concern with liquid hydrogen centered on the "boil-off" rate and the problems of transfer between production lines, storage, and test sites. Designers planned the production facility to achieve a capacity of 6 kilograms of liquid hydrogen per hour, probably the largest plant of its kind in existence. Actual production from September 1948 to June 1949 totaled 336 kilograms of liquid hydrogen, including 2406 kilograms in the last four months of the production period.⁵ Small by later standards, when compared to the hundreds of thousands of kilograms used in Saturn missions, this output represented a notable pioneering effort in the development of liquid hydrogen technology.

The phaseout of Aerojet's production plant and early engine work coincided with the demise of the Navy's hopes for the HATV program under the CEFSR. With cost estimates fluctuating between \$8 million and \$82 million, the Navy hierarchy blanched at the idea of HATV, especially because there seemed to be no immediate military application for it. Undaunted, the CEFSR group tried several routes between 1946 and 1948, including the Army and Air Force; both finally said no. Before the final curtain for the HATV project, CEFSR let a contract to North American Aviation in 1946 to do preliminary studies for a liquid hydrogen rocket engine designed for a HATV rocket 34 meters high and 5 meters in diameter. With a weight of about 46 053 kilograms, including 40 406 kilograms of propellants, the vehicle design specifications called for a propulsion system delivering up to 1 334 400 newtons (300 000 pounds) of thrust at liftoff. The HATV project never materialized as an operational system, although it served a useful function in the accumulation of basic technology that contributed to the successful Apollo-Saturn program. As one acute observer summed it up, "The Navy's HATV had laid the groundwork for the hydrogen engine, the first new advance in rocketry since the V-2."⁶

ENTER THE CENTAUR

The distinction of being the first liquid hydrogen rocket system to reach development went to the Centaur, developed and managed by the

STAGES TO SATURN

Astronautics Division of General Dynamics Corporation. An important aspect of the Centaur story can be traced to the research supported by the National Advisory Committee for Aeronautics (NACA), at its Lewis Laboratory in Cleveland, Ohio.

Researchers at the Lewis facility concentrated on military piston engines during World War II, until NACA abruptly changed the direction of the research efforts. John L. Sloop, one of the Lewis staff members during the "big switch" in the autumn of 1945, recounted the sudden reordering of priorities. "While the laboratory was thus engaged (in military piston engines), others were rapidly progressing in jet engine R&D," he recalled. "The moment of truth came to NACA in 1945 and overnight the NACA management switched the laboratory emphasis from piston engines to jet engines, and the staff was reorganized from stem to stern in the process." The changeover to jet engine, or turbine, research included one or two other esoteric areas of investigation, assigned without warning to many of the lower level supervisors and researchers who had not been informed of the impending changes. Sloop himself went home on the eve of the change, "deeply engaged in writing a report on spark plug fouling." When he reported back to work in the morning, still engrossed in dirty spark plugs, Sloop found his desk gone, himself relocated to a different building, and learned that he was forthwith involved in the problem of cooling rocket engines.

The NACA executives kept the rocket engine business cloaked in obscurity. The political climate at the time was such that "NACA leaders in Washington did not want to proclaim publicly that they were sanctioning work on guided missiles in an aeronautical laboratory, so the group was officially called the High Pressure Combustion Section." This subterfuge remained in force for four years, until Abe Silverstein took over technical management of the Lewis Laboratory in 1949. He acknowledged the significance of the work on rocketry, upgraded the then small group in rank and priority, and officially named it the Rocket Research Branch.⁷

As they surveyed the past work accomplished in rocket research, the former piston-engine and spark-plug experts realized the vast amount of catching up they had ahead of them. When documents became available, the researchers read reports from wartime German work "with great interest," and the research papers of the Jet Propulsion Laboratory also became basic texts. After comparing their inexperience with the more advanced and sophisticated research elsewhere, the rocket group at Lewis made a historic decision to dig into some of the lesser known areas of liquid propellants. By this route, they plowed ahead into the comparatively uncharted seas of high-energy liquid engines—their propellants, combustion characteristics, and cooling problems. After computing theoretical performances of a number of high-energy fuels, the group's first choices narrowed down to hydrazine, diborane, and ammonia, with oxidizers like chlorine trifluoride, hydrogen peroxide, and liquid oxy-

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

gen. In the late 1940s, the group was most attracted to the combination of liquid fluorine oxidizer and diborane as fuel. On the first hot-firing test, the engine melted. Interest in diborane fuels rapidly waned after this unsettling experience, but interest in a fluoride oxidizer continued. After several other candidate fuels were tried and set aside, fluoride and liquid hydrogen came under intensive development in the latter half of the 1950s. The Lewis group kept a file on hydrogen work, so they were aware of the Navy-JPL proposals, the Aerojet liquefaction plant and engines, and the work being done at Ohio State under Herrick Johnston. Consistent with the Lewis group's own activities in high-energy propellants, experimental facilities for liquid hydrogen, among others, were proposed in 1952, but the facility for extensive work in this field was not put into operation until 1956.

The group's work succeeded in technical refinements, such as simulating altitude performance techniques, and in garnering growing support from Lewis Laboratory's director, Abe Silverstein. He developed increasing enthusiasm for liquid hydrogen for applications in high-altitude aircraft, as well as high-energy rockets. Buttressed by Silverstein's endorsement, the rocket research team rapidly progressed in the design of lightweight, regeneratively cooled hydrogen engines of up to 90 000 newtons (20 000 pounds) of thrust. Much of this rapport and enthusiasm was generated during free-wheeling, after-hours bull sessions, hosted by Silverstein, which were honorifically dubbed as "design conferences." The participants unwound and exchanged ideas over beer and pretzels. From one of these diffuse sessions came an important Lewis design known as the "showerhead injector" for liquid rocket engines.⁸

By the late 1950s, the rocket group at Lewis worked with both hydrogen-fluorine and hydrogen-oxygen propellants, fired in a regeneratively cooled engine. Liquid fluorine presented special problems in operations, however, and Silverstein apparently had growing doubts about it. "Later, when he witnessed a hydrogen-oxygen rocket engine operation, the sweetness of the hydrogen-oxygen combination came through to him, and to us, loud and clear," Sloop said. By this time, rocket research at the Lewis Laboratory had increased considerably. Some assignments included preparatory work on propulsion systems for satellites and missions to the moon. Looking back, Sloop and his associates took quiet pride in their contributions to liquid hydrogen engine technology. "We believe that the Lewis work on hydrogen in rocket engines, although not first, was both timely and significant," said Sloop. "We showed that lightweight, regeneratively cooled thrust chambers of 22 250 and 90 000 newtons (5000 and 20 000 pounds) of thrust could operate at very high efficiencies."

Of special significance was the relationship of the Lewis activity to the Centaur program—under the auspices of the Advanced Research Projects Agency (ARPA)—and particularly to the hydrogen engines

STAGES TO SATURN

produced by Pratt & Whitney. One of the ARPA personnel, Richard Canright, also served as a member of NACA's Special Subcommittee for Rocket Engines, and thereby became very familiar with the work at Lewis. A number of key personnel from United Aircraft and Pratt & Whitney, who also worked on hydrogen engines, paid numerous visits to Lewis to see what was going on and to talk with the rocket group there. Eventually, the Pratt & Whitney observers graciously conceded their debt to Lewis's various injector designs, as well as to crucial experimental statistics employed in the development of the XLR-15 engine (an early designation for the RL-10 engine used in the Centaur and, later, in the Saturn upper stages).

Last but not least, the Lewis experience had a definite impact on the direction of the Saturn program very early in the game. After the organization of NASA, Silverstein went to Washington to serve as Director of Space Flight Development. In anticipation of the Army's transfer of Saturn to NASA, NASA's Associate Administrator tapped Silverstein to chair a special interagency committee to consider the scope of Saturn's development, and to submit recommendations on goals and implementation, particularly the configuration of the upper stages. "With a persuasive chairman occupying a key position and sold on hydrogen-oxygen, it is not surprising that the group recommended that the upper stages of Saturn be hydrogen-oxygen," observed Sloop, somewhat sardonically. Perhaps the most notable contribution of the Lewis rocket group, he concluded, lay in its influence on the decision that shaped the design of the Saturn's upper stages.⁹

CENTAUR: THE LEGACY OF A PIONEER

The ultimate goal and purpose of astronautics is to gain for man himself access to space and then to other worlds. The guided missile does not carry a man. It is a bridge between the space-flight concepts at the beginning and the space-flight reality yet to come. Achieving this reality requires yet another stepping stone: the high-energy upper stage which is boosted aloft by the missile and which, in turn, places the manned spaceship within the reach of the planet to be explored. The upper stage, a logical follow-on to the missile, now takes its place within the development chain designed at getting man to the stars. This, then is Centaur . . .

This slice of slightly overripe prose, a product of Centaur's public relations office,¹⁰ manages to summarize some characteristic trends in America's space program. The Centaur effort, particularly the propulsion system, illustrates both the triumphs and the tribulations of liquid hydrogen technology. The effort also highlights some of the differentiations found in rocket vehicles such as the Centaur, S-IV, and S-IVB on the basis of a type of propellant system common to all three.

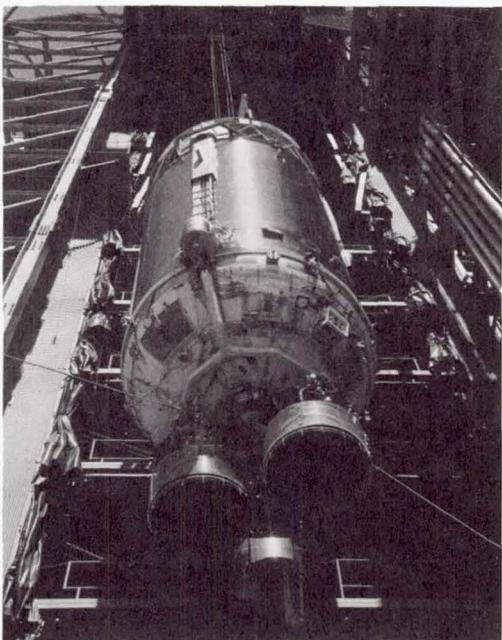
With Atlas operational and successful, General Dynamics/Astronautics (GD/A) began to consider its uses as a launch vehicle for space missions.

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

By adding on a second stage, the company's planners hoped to achieve a design capable of heavier payloads than currently employed as missile warheads. Serious studies began in 1956, contemplating payloads like high-altitude satellites for early missile warning, global reconnaissance, weather scanning, and communications. Such payloads required a very-high-energy stage to boost them into orbit. The GD/A investigating team chose liquid oxygen and liquid hydrogen as propellants.¹¹ The team had looked into a number of high-energy propellant combinations, including fluorine as an oxidizer, but fluorine did not promise a significant gain in specific impulse and performance. Besides, the choice of liquid oxygen would continue the use of well grounded operational technology, and save considerable time and development efforts. When it came to the choice of fuel, the team again considered several options, but chose to rely on liquid hydrogen, because its specific impulse came closest to the upper limits that could be attained with chemical propellants. Selection of liquid hydrogen was a knowledgeable gamble: Pratt & Whitney was not a total stranger to this new area of cryogenic technology. In the mid-1950s, the Air Force had been working on experimental jet engines using LH₂ fuel, and Pratt & Whitney had been deeply involved in this research. Even though liquid hydrogen entailed problems as a jet engine fuel, many company engineers viewed hydrogen as the most promising fuel for applications in future rocket technology, either for chemical or nuclear propulsion. "Also," the company noted, "this vehicle would offer a favorable starting point for the development of this technology, because of its limited size and because none of the missions yet required very long storage periods in space, as would be the case with future hydrogen-powered vehicles."¹²

In its formal proposal, GD/A outlined a program with potential for various high-altitude satellites for strategic use, adding the possibilities of deep-space probes and even manned orbital configurations. As a launch vehicle, the GD/A specifications recommended a modified Atlas ICBM first stage with conventional liquid oxygen and RP-1 propellants, and a four-engine second stage (still on the drawing boards) using oxygen-hydrogen as oxidizer and propellant. It was the proposed second stage that appealed to the USAF Air Research and Development Command, who selected it from several unsolicited proposals involving satellites for communications. On 14 November 1958, GD/A received a contract to manufacture a total of six hydrogen-oxygen upper stages for ARPA, marking the formal origins of the Centaur program. The Air Force tagged the Atlas-Centaur as its launch system for Advent, a synchronous-orbit equatorial communications satellite.

While GD/A tooled up for the fabrication of the vehicle's tanks and structure in San Diego, Pratt & Whitney started to work on the engines at its West Palm Beach facility in Florida. One of the basic problems was getting an adequate quantity of liquid hydrogen for R&D work on the



A Centaur stage with the two RL-10 liquid-hydrogen-fueled engines used on the S-IV stage of Saturn I.

propulsion systems. In conjunction with development and testing of the Pratt & Whitney engine, the USAF planned a production facility for liquid hydrogen near Pratt & Whitney's West Palm Beach location. As the program developed, and the Centaur's engines were conscripted for use in NASA's space program, engine testing also occurred at Marshall Space Flight Center (MSFC), Lewis Research Center, Edwards Air Force Base, and two other Pratt & Whitney Centaur test areas in California. The Douglas Aircraft Rocket Test area near Sacramento also test-fired the Pratt & Whitney engines on the six-engined S-IV upper stage of the Saturn I.¹³

Even before the Silverstein recommendations in December 1959, the channels that brought high-energy hydrogen-oxygen engines into the Saturn program had begun to converge. At Huntsville, Alabama in the spring of 1959, preliminary upper-stage vehicle studies for the Saturn program included the Centaur as a third stage. The final recommendations of the Silverstein committee, coupled with the prior interest in the high-energy Centaur, finally locked liquid hydrogen into the Saturn's development. Oswald Lange, a key figure in the early Saturn program at MSFC, considered the Centaur's engines "a major technological breakthrough." Before the Army Ballistic Missiles Agency phased out, the ABMA Saturn project designated the Pratt & Whitney engines as the propulsion system for the Saturn's third stage. "The early choice of Centaur," said Lange, "had far-reaching effects on the Saturn development program."¹⁴ Following the organization of the National Aeronautics and Space Administration, Centaur was assigned to the civilian space program under the aegis of NASA's MSFC. Centaur was ticketed as one

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

of the upper stages for Surveyor and Mariner lunar and planetary missions, and MSFC began to plan Centaur's role in the development of the Saturn vehicles. MSFC's role in Centaur management was somewhat controversial. Some people at NASA Headquarters argued that the Air Force should manage the Centaur engine because of its original military mission as a communications-satellite booster. At Huntsville, the Centaur engine effort might have been submerged by the Saturn program.¹⁵

The Saturn program's association with the development of liquid hydrogen-oxygen engines officially commenced on 10 August 1960, when MSFC signed a contract with Pratt & Whitney for the development and production of an engine, known as the LR-119, to be used in the S-IV and S-V stages of the C-1 vehicle envisioned in the Silverstein report. Designed to give 66 700 newtons (17 500 pounds) of thrust, the LR-119 was an uprated version of an early Centaur engine concept, the LR-115. Problems with the development of this new version led to the reconsideration of the original Centaur propulsion system, and in March 1961, the management of MSFC recommended the design of a liquid-hydrogen S-IV stage using the original LR-115 hardware. To compensate for the loss of thrust, MSFC decided to cluster six engines instead of four. On 29 March 1961, NASA Headquarters concurred, and the new six-engine cluster became the official configuration. In the course of development, Pratt & Whitney assigned various designations to the basic liquid hydrogen-oxygen engine. The final design, RL-10-A-1, replaced both the LR-115 and 119, and the RL-10 configuration became standard for both the Centaur and S-IV vehicles by 1961. An early version of the RL-10 design went through its first successful firing in August 1959, and by the winter of 1961, technicians finished the last of the RL-10-A-1 preflight rating tests. The engine's 66 700 newtons (15 000 pounds) of thrust performed 30 percent better than similar designs using hydrocarbon fuels. The A-1 designation identified a test article; on 9 June 1962, Pratt & Whitney finished the preliminary flight rating tests on the RL-10-A-3, intended for installation in operational flight versions of the second stage of the C-1 launch vehicle.¹⁶ The nation's first operational liquid hydrogen-oxygen engine was cleared for production.

THE RL-10 PROPULSION SYSTEM

Pratt & Whitney engine design unquestionably benefited from the work at Lewis during 1953–1957, especially the virtues of regenerative cooling with liquid hydrogen.¹⁷ Pratt & Whitney added other innovative features. The Saturn program's RL-10 engines were mounted on the S-IV booster manufactured by Douglas as the second stage for the Saturn I. In physical terms, the RL-10 was about as tall as an average man. Its major components included the thrust chamber, fuel and oxidizer

STAGES TO SATURN

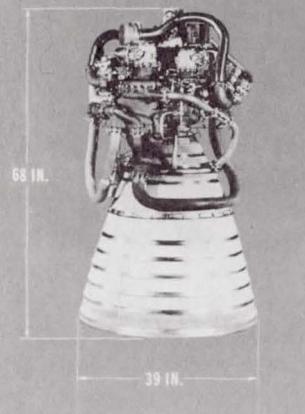
turbopump assembly, liquid oxygen flow control valve, spark ignition subsystem, thrust control assembly, and miscellaneous control valves.

The contours of the nozzle configuration owed much to the influence of applied mathematics. Pratt & Whitney wanted a nozzle designed for optimum size and weight in relation to performance, but liquid hydrogen technology was so new that few ground rules were available. Applied math bypassed a lot of costly hardware experimentation, and Pratt & Whitney claimed that the procedures established during the effort became widely used within the rocket propulsion industry.¹⁸

The injector, part of the thrust chamber assembly, featured a porous injector face, which was an important innovation. The RL-10 injector strongly resembled a large dish with a shallow, concave surface. Fabricated from material that looked like a heavy screen, the injector's propellant orifices poked through the mesh in concentric rings. The porous injector face did, in fact, consist of layers of stainless steel mesh, produced by a carefully controlled sintering procedure that caused the layers of mesh to become a coherent structure without melting. A controlled flow of gaseous hydrogen filtered through, cooling the injector face and reducing thermal stresses. The material, called Rigi-Mesh by its supplier (the Pall Corporation), apparently originated as a filter used in nuclear research. The product had been extensively used in hydraulic and pneumatic filters in aircraft and jet engines, where extreme vibration environments, high temperatures, and other operational requirements discouraged the use of nonmetallic filters. How Rigi-Mesh was first suggested for use in rocket thrust chambers is unclear. In any case, the Pratt & Whitney injector approach, using the porous mesh face, was a distinct improvement over conventional, flat-face injectors that Lewis Research Center had used.¹⁹

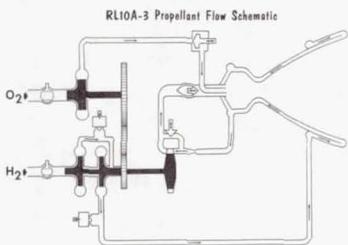
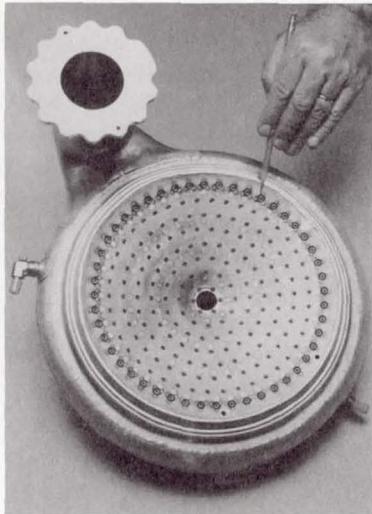
The fuel and oxidizer pumps were driven in a "boot strap" arrangement from a turbine assembly rated at 479 to 513 kilowatts. The propellant pumps consisted of a two-stage centrifugal fuel pump and a single-stage centrifugal oxidizer pump. General Dynamics/Astronautics described the engine's turbopump as the key to operating the RL-10 production version, in which the "boot strap" sequence used gaseous hydrogen. At the start, liquid hydrogen trickled through the turbopump and down through the thrust chamber tubes of the regeneratively cooled engine. Even before the ignition sequence and main stage operation, the flowing liquid hydrogen became gaseous, and could be forced back through the turbopump with enough pressure to start it. This pressure set the hydrogen fuel pump in motion, and a gear train from the hydrogen turbine's main shaft began to drive the liquid oxygen pump—the "boot strap" sequence. After the start of combustion, the heat produced enough gas in the chamber walls to drive the high-speed turbine and also to maintain the combustion level.²⁰

RL10 ENGINE

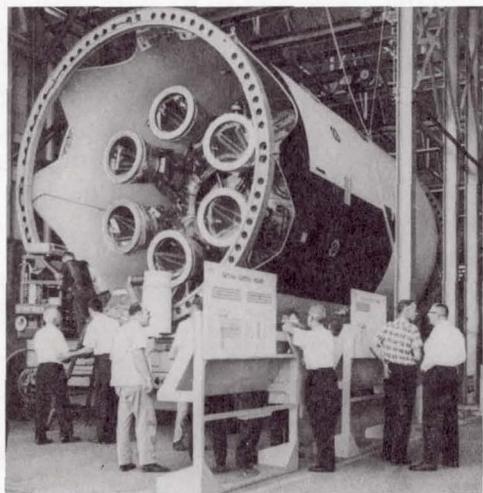
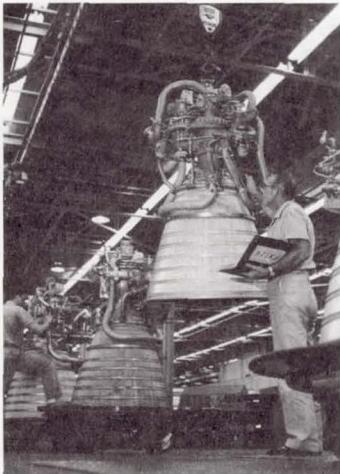


THRUST - 15,000 LB (ALTITUDE)
THRUST DURATION - 470 SEC
SPECIFIC IMPULSE - 433 SEC
ENGINE WT DRY - 298 LB
EXIT-TO-THROAT AREA RATIO -
40 TO 1
PROPELLANTS - LOX & LH₂
PROPELLANT FLOW RATE -
35 LB SEC

CONTRACTOR -
PRATT & WHITNEY
SYSTEM - SAT I S-IV (6 ENGINES)
CENTAUR (2 ENGINES)



Top left, the RL-10 statistics; above, right, the RL-10 injector, with a textured surface of Rigidmesh for transpiration cooling. At left is a schematic of RL-10 propellant flow. At bottom left is the RL-10 production line at Pratt & Whitney in Florida. Bottom right shows a Saturn I S-IV second stage with its cluster of six RL-10 engines.



STAGES TO SATURN

This design offered two main advantages. First, the engine did not require a third propellant or a bipropellant to service a gas generator system (at a weight penalty) for the turbopump. Second, the designers obtained an efficient performance advantage because the hydrogen gases, after driving the turbine, were exhausted into the combustion chamber. All propellants, then, contributed directly to maximum thrust and highest specific impulse. The operation of the turbomachinery incorporated another interesting design feature. The RL-10 was the first production engine to use liquid hydrogen in place of conventional lubrication systems.²¹

During the test program, NASA and contractor personnel pushed the design to extremes to verify the engine's capability. Designed for a total firing time of 470 seconds, test engineers piled more than 3.5 times that duration onto one engine, running it for a total of 1680 seconds. Some of the test engines successfully operated through 5 to 70 separate firings with no maintenance or replacement of parts, equivalent in some instances to 10 round trips to the moon. "This philosophy of 'limits' testing has proven successful in developing an engine with a high reliability and a high degree of confidence," explained key personnel in MSFC's engine program office. They characterized the pioneering RL-10 as a system of notable sophistication and versatility.²²

ORIGINS OF THE J-2 ENGINE

Because of the known high-energy qualities of hydrogen as a fuel, modern rocket propulsion engineers manifested a continuing interest in liquid hydrogen as an attractive rocket propellant, able to lift payloads at a very favorable fuel-to-payload ratio. The potential of the liquid hydrogen RL-10 engine was encouraging; nevertheless, designers were thinking ahead of the RL-10's 67 000 newtons (15 000 pounds) of thrust to even heftier propulsion systems. In the fall of 1959, various NASA studies and contracts already included examination of 665 000-newton (150 000-pound) thrust engines, used singly or in clusters, which burned LOX and LH₂. When very large space vehicles came into consideration, NASA began to revise its thinking toward even larger LH₂-fueled engines for high-energy upper stages—engines rated at 890 000 newtons (200 000 pounds) of thrust. Such a remarkable goal achieved official sanction during the deliberations of the Saturn Vehicle Team, better known as the Silverstein committee, which finished its work and reported its recommendations to NASA on 15 December 1959.²³

Following the Silverstein committee's recommendations, a source evaluation board was formed to nominate a contractor. The board included a pair of special teams—a technical evaluation team and a business evaluation team—to examine proposals on two separate levels.

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

Members, who met in Washington for six weeks, were chosen from Marshall, Lewis, and NASA Headquarters. The full board, chaired by MSFC's Hermann Weidner (a Peenemuende veteran and a senior MSFC propulsion engineer), submitted its final recommendation to NASA Administrator Glennan for approval. Glennan made the final announcement. In competition with four other companies, Rocketdyne Division of North American Aviation won NASA's approval on 1 June 1960 to develop a high-energy rocket engine, fueled by liquid oxygen and hydrogen, to be known as the J-2. Specifications for the liquid-hydrogen engine originated at MSFC, and the contractor then went to work on the initial design concepts and hardware. At every step of the way, the contractor and the customer (MSFC) exchanged information and ideas derived from earlier programs, modifying them for the requirements of the LH₂ engine technology, and devising new techniques to implement the design goals of the new rocket powerplant.

The final contract, negotiated by Rocketdyne in September 1960, included an especially notable feature. For the first time, a high-energy, high-thrust rocket engine contract specified a design to "insure maximum safety for manned flight." Beginning with the first specifications through the subsequent stages of design, development, and final qualification, planning for manned missions became a mainline theme for Rocketdyne engineers. Other engines in NASA's space program stemmed from propulsion systems engineered for unmanned satellites or ballistic missiles such as the Vanguard, Redstone, Atlas, and Thor. From the start, exceedingly stiff reliability specifications for the J-2 reflected the engine's role in a manned mission. Reliability reviews began at the drawing board stage, and follow-up tests to verify the preceding test and design specifications continued in relentless succession. The technical management organization established to monitor the J-2 development consisted of three major groups. First, the design review board scrutinized each part of the J-2, analyzed it from a technical viewpoint, and investigated all of its design factors. Next, a reliability task force developed statistical methods tailored specifically to proposed test programs for the engine. Finally, all elements dovetailed in the Performance Evaluation and Review Technique (PERT), a reporting system used by the overall program management team.²⁴

EARLY J-2 MILESTONES

Rocketdyne launched the development of the J-2 with an analytical computer model that simulated engine operations and aided in establishing design configurations. One outgrowth of the model, a full-sized mockup with which to judge position of all components, remained an important tool throughout the J-2 program.²⁵

STAGES TO SATURN

Rocketdyne's physical plant and long experience as a rocket engine manufacturer allowed the company to respond quickly. The main complex at Canoga Park, in the northwest sector of Los Angeles, combined engineering offices with elaborate laboratories for preliminary R&D. Development and production of the F-1 and the H-1 (and its immediate predecessor, the S-3D), coupled with extensive experimental work on advanced propulsion systems, equipped the company with excellent facilities and experienced R&D teams. Rocketdyne carried out J-2 firing tests and major-component tests at its Santa Susanna Field Laboratory, a rambling network of test stands and test cells set up in canyons and arroyos of the Santa Susanna Mountains, directly above the manufacturing area at Canoga Park. In days gone by, the canyon walls and gulches echoed with the drumbeat hooves of galloping horses and the sharp crackle of gunfire as Hollywood production crews cranked out yet another Western epic. Now the arroyo walls enveloped test beds for rocket engines, the steep slopes shielding the rest of the test areas and their crews in case something went wrong and an engine blew up. A visit to the surrealistic environs of Santa Susanna made a lasting impression. It was a tortured, sun-baked tumble of rocks and scraggly underbrush, with the separate test areas connected by long runs of piping for water and miscellaneous esoteric liquids required in rocket development. The pipes erratically twisted their way over the boulder-strewn landscape and up to the test fixtures—austere monoliths of concrete and stark steel girders jutting into the hot California sky. It seemed a fitting environment for the exotic world of rocket engine testing.²⁶

Within two months of winning its contract, an R&D team put together the J-2's first experimental component, a full-scale injector. Using a temporary test facility at Santa Susana, Rocketdyne technicians conducted the first hot-firing tests on 11 November 1960, to check out the workability of its design. In simultaneous programs, the company began developing means to test engines as well as engine components, modifying test stands as required. A large vacuum chamber to test engine subsystems under simulated space conditions was completed. By the end of 1960, the manufacturing planners, with an eye on problems encountered during the early design and phase, began to try to resolve some of the sticky manufacturing problems looming on the horizon. The schedule was obviously getting tighter as the research and development teams began the fabrication and assembly of the first experimental components and emplaced them in the test cells. Inaugurating Rocketdyne's first test facility built exclusively for the J-2 program, workers activated a component test cell in November 1961, and engineers began trial runs of the J-2 liquid hydrogen and liquid oxygen turbopumps. Early in 1962, only 18

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

months after contract award, Rocketdyne conducted the first engine system test for ignition, lasting 2.57 seconds. The test unit used an uncooled thrust chamber with the turbopumps driven by externally supplied gaseous hydrogen, instead of using the engine's internal gas generator.

Drawing further on its considerable fund of experience in developing rocket engines for Army and Air Force programs, Rocketdyne personnel fabricated additional test components of the new J-2 in remarkably short order, and began to piece together the first experimental engine in the closing months of 1961. Technicians made final checks on the engine in the company's Canoga Park complex during January 1962 and stowed it on a truck, to be driven up the winding mountain to the Santa Susanna Field Laboratory. Short-run tests began the same month and continued through the summer. Technicians were achieving full-thrust testing of 50 to 94 seconds duration by early autumn, and on 4 October 1962, Rocketdyne successfully ran the engine through a long-duration test of 250 seconds.²⁷

During the early developmental period in J-2 testing, the engine's place in Saturn rocket configurations also stabilized. In July 1962, NASA and Rocketdyne concluded contracts for continued development and formalized the production agreements for the J-2 through 1965. About the same time, NASA announced plans for a new two-stage vehicle, the Saturn C-1B (later the IB) for operations leading to Earth-orbital missions with a full-sized Apollo spacecraft.²⁸ The J-2 engine was intended to power the S-IVB stage of two Saturn vehicles—the second stage of the Saturn IB and the third stage of the Saturn V. In addition, a cluster of five J-2 engines was also planned for the S-II second stage of the three-stage Saturn V vehicle, making the J-2 the most used cryogenic propulsion system in the Saturn program.

NASA and Rocketdyne signed a contract for 55 engines and development of appropriate support technology on 1 July 1962. Later in the month, Rocketdyne announced its plans for the construction of two new manufacturing buildings for the Saturn engines, including the J-2. The buildings were completed in record time; the company moved in just a year later. In November 1963, Rocketdyne began delivery of five engine simulators. Up to the point of actual firing, the simulators played an important role in the process of electrical and mechanical design of the ground support equipment furnished by Rocketdyne, and permitted technicians to work out the interfacing details involved in mounting the engine to the appropriate stage—the S-II stage manufactured by North American, or the S-IVB stage manufactured by Douglas. Ground support equipment, operating consoles, and special handling gear for the

STAGES TO SATURN

engines and propellants were used in Rocketdyne's own manufacturing and test operations in California, at other test sites (Marshall and Mississippi Test Facility), and in launch operations at Cape Kennedy.²⁹

THE J-2: LEGACIES AND INNOVATIONS

Confident with the test results during 1962, Rocketdyne began to release the first production drawings to the manufacturing shops early in 1963. The J-2 engine emerged from the drafting boards as a self-contained propulsion system—a significant concept because the J-2 had to start in flight, shut itself down, then (in some versions) restart in orbit. Explaining the engine at a meeting of the American Institute of Aeronautics and Astronautics, Paul Fuller (Rocketdyne's project manager for the J-2 in 1965) stressed the effort given to the self-contained design philosophy. "The J-2 engine is not just a rocket engine supplying thrust for the vehicle, but is a fully integrated propulsion system," Fuller emphasized. "The engine provides all functions important to the vehicle's operation and mission capability." For this reason, engine and stage operation systems were closely integrated. To maintain tank pressure and still control the weight of the vehicles, the S-IV and S-IVB pressurized their fuel tanks by tapping hydrogen gas from the fuel manifold on the thrust chamber. To keep up pressure in the LOX tank, designers included a heat exchanger on the oxygen pump exhaust duct. In the S-II second stage, hot oxygen from the exchanger served as the pressurant, while in the S-IVB, stored helium ran through the exchanger and back into the LOX tank. These systems eliminated the need for other pressurants along with their extra weight and complexity.

The S-IVB, with a programmed restart in Earth orbit, included a "self-servicing" concept for the reignition sequence. The helium tanks included enough gas for the duration of the mission, but to get enough hydrogen gas to accelerate turbomachinery for the restart cycle, the engine system automatically diverted 1 kilogram of LH₂ from the fuel system for storage in the depleted hydrogen start tank. To ensure proper functioning of the entire system during a mission, the engine's designers included integral instrumentation on the J-2 to monitor engine functions on 72 different channels.³⁰

For the integrated engine system philosophy, designers of the J-2 borrowed from many earlier liquid propellant engines, including the liquid hydrogen technology of the RL-10 program, and added a few innovations along the way. In the process, technicians and manufacturing engineers learned to cope with the problems generated by the J-2 as a newer and much larger generation of liquid-hydrogen engine systems.

Like the RL-10, the J-2 injector had to promote stable, controlled burning. But the 890 000-newton (200 000-pound) thrust J-2 burned

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

much greater quantities of cryogenic propellants than the 67 000-newton (15 000-pound) thrust RL-10. When Rocketdyne started work on the injector in 1960, the company tried a design familiar to its engineers, and built flat-faced copper injectors similar to LOX-RP-1 designs. The heat fluxes of LOX-LH₂ designs turned out to be much different at the injector face, and the injectors started burning out. Bob Pease, an MSFC propulsion engineer who monitored some of the early tests, recalled that green flames shot out of one injector as the flame front started burning its way through the copper.

As one Marshall engineer observed, it was the general nature of a contractor to be reluctant to take on a competitor's innovation. Rocketdyne's injectors kept burning out, but the company seemed adamant against incorporating the porous injector face style of Pratt & Whitney's RL-10. Rocketdyne had been experimenting with this type of injector at NASA's insistence, and Marshall began to feel that their J-2 contractor needed a shove in this direction, instead of the persistent nudges delivered by MSFC up to this point. Lewis Research Center had all the information and hardware samples for the porous injector face. Jerry Thomson and other Marshall engineers dragooned Rocketdyne personnel into a special trip to Lewis in 1962 to look at the samples, and pressured Rocketdyne to use Rigi-Mesh in the injector face. With Rigi-Mesh adapted to the J-2, the problems of injector face burning disappeared.³¹

Still, Rocketdyne's larger engine and its operational characteristics presented difficulties in manufacturing. The successful design led to the next set of problems: how to "mass produce" a rocket engine injector with more than 600 uniform injection posts. After some trial and error, manufacturing engineers finally evolved a method of producing an injector with 614 uniform posts from a single piece of metal, using a special technique of electrical discharge machining. Fuel from the upper fuel manifold flowed into the combustion area through fuel orifices designed to be concentric with the oxidizer orifices. Design of the injector and angles of the orifices was calculated for highest combustion efficiency. As the hydrogen passed through the injector to the annular orifices, 5 percent of the flow seeped through the porous injector face, acting as a coolant to reduce thermal stresses created by the roaring combustion chamber.³²

The J-2's thrust chamber consisted of several hundred steel tubes, designed and shaped according to data derived by computer. The computer helped solve the frustrating interplay of "the general energy equation, momentum equation, continuity equation, equation of state, and heat balance equation across tube walls." The readout of the computer proved to be very accurate, the final design of a tapered, formed tube bearing very close conformance with the original analytical model. Designers made optimum use of the marvelous facility of LH₂ for heat transfer in designing the thrust chamber. Fuel entered the chamber

STAGES TO SATURN

through a manifold at the chamber's midpoint, making a one-half pass down through 180 tubes on the outside, then up the inside of the chamber's throat in a complete pass through 360 tubes to the fuel injector. The liquid hydrogen entered the tubes at -253°C (-423°F) and warmed up in passage to "only" -162°C (-260°F), at which point it became gaseous. The design of the tubes permitted extremely wide variations in LH_2 velocities, ranging from 18 meters per second at the bottom of the pass at the chamber's edge to 300 meters per second at the throat, and 240 meters per second at the injector entry ports. At different points within the tubes, cross sections varied correspondingly to accommodate changes in density and flow rates.³³ With so many variables in the design, it is no wonder that the computer played such a pivotal role in engine development.

Turbopump design borrowed liberally from North American's experience in manufacturing jet aircraft engines and the early rocket engines for the Air Force. As in jet engines, the turbopump turbine blades featured a "fir tree" attachment technique. The bases of the blades were tapered and notched, giving them the silhouette of an inverted fir tree. Centrifugal forces in the turbopumps were terrifically high, and the notched blades kept them securely in place. From the Atlas program, Rocketdyne borrowed turbopump inducer designs and the inducer tunnel assembly, but many, many more components had to be conceived and fabricated to the characteristics of the new LOX-LH_2 technology.

In designing the J-2 turbopumps to deliver propellants to the injector and the combustion chamber, the system was split into two different components, the LOX pump and LH_2 pump mounted separately on either side of the combustion chamber. This approach avoided compromises in the efficiency of either pump and eliminated a complicated set of gears to run both pumps from a single shaft. On the LOX side, the J-2 used a radial pump, common to most rocket engines, which operated in the 6000 revolutions per minute range. The LH_2 pump, by contrast, used a pump uncommon in large thrust engines, at the time—a seven-stage axial flow design with an operating capability of over 25 000 revolutions per minute. With proper calibration, the pumps delivered propellants to the thrust chamber at a rate of 2.3 kilograms of liquid oxygen to 0.4 kilogram of hydrogen.³⁴

Power for the turbopumps came from a two-stage, velocity-compound turbine fired by a gas generator. The original design for the J-2 engine envisioned a "tank-head" start, in which pressure from the fuel tanks started the gas generator. Once in operation, the feed pressures and power increased as the turbopump attained its operational limits, drawing propellants from the tanks. The "tank-head" start was attractively simple but turned out to be too slow to be used in flight operations for the Saturn. So the turbine power system acquired augmentation for the spinup of the gas generator, using a spherical tank to store compressed

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

hydrogen gas with a storage capacity of 0.1 cubic meter. Gas from the hydrogen sphere started the gas generator and achieved rapid acceleration and operation from the start. This "gas-spin" start could be initiated at will during the flight, important for reignition of the S-IVB stage in Earth parking orbit. The only requirement involved a brief cycle during the engine run, in which hydrogen gas was tapped to recharge the hydrogen sphere.³⁵ The design of the hydrogen storage tank constituted a unique feature of the J-2 engine: it incorporated a "tank within a tank," combining hydrogen storage with a helium storage tank. The helium, required for the pneumatic control system, tended to vent off unless kept under pressure at a low temperature. In a neat solution to the problem, Rocketdyne designed the helium storage tank as an integral unit inside the hydrogen start tank, and thereby saved space as well as weight. Both tanks were filled on the ground prior to launch—the outside tank with hydrogen, the inner tank with helium.³⁶

The 1½-pass fuel circuit permitted another design variation, in the disposal of the exhaust gas from the turbopumps. The gas delivered from the gas generator to the propellant turbopumps passed in sequence through the hydrogen axial flow turbines, then through a duct into the radial turbine of the LOX pump. The series arrangement yielded a very high efficiency and permitted easy control of the thrust and mixture ratios. Having already performed double duty in both the fuel and oxidizer turbopumps, the turbine gas exhausted into the thrust chamber to be used as fuel. In this way, the engine handled the turbine exhaust very conveniently and enhanced the engine's specific impulse at the same time.³⁷

The high speeds at which the J-2's moving parts functioned required some special lubricants, which were acquired from the propellants themselves. Ball bearings in the turbopumps present special problems in lubrication—particularly the super-cold LH₂ pumps. Normal lubricating oils proved troublesome because of the extremely low temperatures of cryogenic operation, so Rocketdyne built the LOX and LH₂ turbopumps to have their ball bearings lubricated by the respective propellants. At Ohio State University, Herrick Johnston first demonstrated the potential of LH₂ lubricants. The use of cryogenic lubricants in the RL-10 paved the way for this lubrication in the J-2.³⁸

PRODUCTION AND TESTING

In May 1963, production lines for the operational model of the J-2 went into full swing, but concurrent testing programs at Rocketdyne and at MSFC were also maintained throughout the production run. Engineers from both the contractor and the customer were on hand when Douglas began firing up S-IVB stage hardware. The first production

STAGES TO SATURN

engine, delivered in April 1964, went to Douglas for static tests on the S-IVB battleship stage at the Douglas test facility near Sacramento, California.

The first full-duration static test of 410 seconds occurred on the battleship stand late in December. The mission requirements of the third stage for the Saturn V called for an application of 500 seconds, but each engine possessed a minimum usable life of 3750 seconds. Even so, the testing program often forced the engines beyond this. L. F. Belew, MSFC engine program manager, characterized the philosophy of "limit testing" as a combination of requirements for manned flight and cost control. "A major emphasis is placed on limits testing as a means of demonstrating reliability and confidence without a prohibitively large test sample," he explained.³⁹

Intensive engine testing, including tests on MSFC's new S-IVB test stand in Huntsville, and flight rating tests of the 890 000-newton (200 000-pound) thrust engine for the Saturn IB and Saturn V at Santa Susanna Field Laboratory, continued throughout the summer of 1965. The last of the stringent qualification tests of the J-2 engine occurred from December 1965 into January 1966, conforming very closely to Belew's estimate. The J-2 proved its ability to perform well over its specified operational range. One engine ignited successfully in 30 successive firings, including five tests at full duration of 470 seconds each. The total firing time of 3774 seconds represented a level of accumulated operational time almost eight times greater than the flight requirements. As successful single engine tests moved toward their climax, integration tests of the propulsion system with the S-IVB accelerated with the availability of more production engines. Time schedules for testing the flight stages of the S-IVB became ever more pressing. The first operational flight, AS-201, was scheduled in early 1966 for the Saturn IB using the S-IB first stage and the S-IVB as the second stage.

At Sacramento, the first tests of S-IVB-201 in July 1966 were inconclusive when a component malfunction in one of the pneumatic consoles prematurely ended the test after a successful propellant loading and automatic countdown. Test conductors regained confidence on 8 August, when the S-IVB-201 performed beautifully on a full-duration firing of 452 seconds. The test commanded extra attention because of the first use of computers to control the entire operational sequence, including automatic checkout, propellant loading, and static firing.⁴⁰ The successful test was no fluke. On 26 February 1966, AS-201 went through a flawless launch.

In July 1966, NASA confirmed J-2 production contracts through 1968, by which time Rocketdyne agreed to finish deliveries of 155 J-2 engines. The new contract included an uprated model of the J-2 engine with a thrust of 1 023 000 newtons (230 000 pounds). Rocketdyne began work on the uprated version in 1965 and delivered the first engine to

MSFC for testing during the spring of 1966. Mission planners intended to use the new engine in the second stage of the Saturn IB beginning with AS-208, as well as the second and third stages of the Saturn V beginning with AS-504. Meanwhile, an intensive test program continued. Following a preliminary series of simulated altitude tests using Rocketdyne facilities, a more stringent series of tests was conducted using the advanced equipment of the Arnold Engineering Development Center. The center was run by the Air Force at Tullahoma, Tennessee, not far from MSFC. Specialists at Arnold ran a series of altitude tests on J-2 engines for the S-IVB/IB stage and followed up with an equally successful test series on engines for the S-IVB/V in March 1967. Using facilities that duplicated temperatures and environmental conditions at 305 000 meters, Arnold cooperated with NASA on a string of initial start, stop, and the crucial reignition sequences. Throughout the year, Rocketdyne continued to test and verify the J-2 reliability at Santa Susanna. The company's research and development program included 203 separate tests on the J-2, accumulating a total of 33 579 seconds of firing time. In a concurrent program, production engines from the assembly lines in the valley kept rolling up the mountainside in trucks for their production qualification tests.⁴¹

J-2 PROBLEMS AND SOLUTIONS

Development of the J-2 engine turned up the inevitable gaggle of problems to perplex project designers, engineers, and workers. In using cryogenic propellants, it was obvious that great care was needed to ensure installation of very efficient insulation at critical points to control thermal losses. In the case of most early rocket technology using LOX as the oxidizer, the problem was not immediate. Designers simply took advantage of the fact that LOX components had a tendency to frost over. The frosty coating worked surprisingly well as natural insulation—so well that many components were designed without insulation from the start. The super-cold liquid hydrogen permitted no such easy design shortcuts. When air touched the extremely cold LH₂ surfaces, it did not frost, but actually liquified. As a result, streaming liquid air not only became an annoyance, but also created a serious heat leak. For J-2 parts operating with LH₂, it became imperative to provide adequate insulation. Vacuum jackets sufficed for most of the liquid hydrogen hardware, and similar treatment, or moisture-sealed insulation, worked for pump fittings and ducts. The main LH₂ inlet duct, however, presented a more intricate challenge. The duct had to move with the gimbal action of the engine through 10.5 degrees, maintaining a full flow of fuel all the while. With a diameter of 20 centimeters, and a length of 53 centimeters, the duct also experienced extension and compression of -11.4 centimeters, with a

STAGES TO SATURN

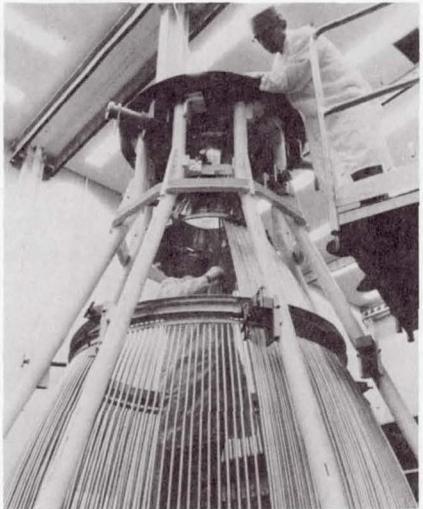
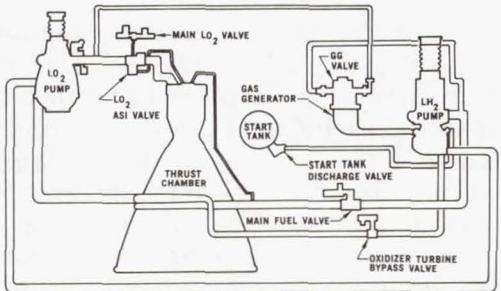
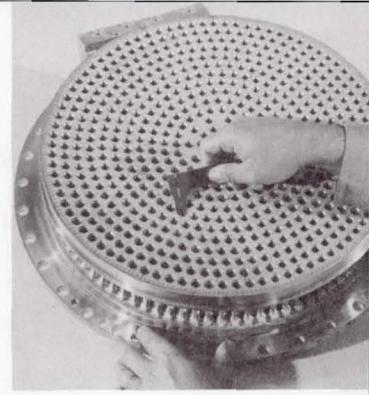
twisting, angular movement. The final design featured a vacuum jacket built like a double bellows, stabilized with externally mounted scissorlike supports. Top engine program managers from NASA agreed that the vacuum-jacketed flex inlet lines marked a significant design achievement in the J-2.⁴²

The prickly, minute, intricate problems of liquid hydrogen technology followed the design engineers down to the last details of the J-2, including the myriad of joints where different ducts, tubes, and lines met each other or fastened to specified engine parts. At each juncture there existed the danger of an LH₂ leak and a devastating explosion. Rather laconically, W. R. Studhalter, one of Rocketdyne's engineers in the J-2 program, summed up a tedious, frustrating job. "The static seals for hydrogen had particular design attention," he said, "not only to prevent loss under vacuum operation, but to prevent hazardous mixing of hydrogen with air during sea-level testing and handling." To alleviate sealing complications, he continued, "the engine design has concentrated on the elimination of joints requiring sealing by a uniquely complete utilization of welded connections." Some seal points were not suitable for welding, and with specifications for zero-measurable leakage, the J-2 team met the problem with a device known as a "pressure-actuated combination seal." "This seal has such excellent demonstrated performance that it is used throughout the J-2 engine," said Studhalter, "not only for liquid hydrogen but for liquid oxygen, helium, and generator gas." The J-2 had 112 various seals, mostly for instrument connections. Most were small, although the biggest installation required a comparatively large unit for the thrust chamber-injector seal point.⁴³

Modifications never seemed to end. Marshall engineers noted that they could test components to exhaustion, but "you would never know for sure they would work until you put them together in the engine." Even if two engines tested successfully, a new problem might show up on the third. There was a lot of "cut-and-try" work to solve these complications, and the engine men admitted that they were not always sure which "fix" corrected a problem—or created a new one. The engineers were reconciled to a process of changes, of trying to find out what went wrong (or what could go wrong), and trying to correct the difficulty. "Happiness should be finding a failure, rather than not finding a [potential] failure," said MSFC's Bob Pease. It was accepted that many problems would be caught after the engines were already in production. The Saturn program always needed production hardware to meet schedules, and the stage contractors needed engines as early as possible to verify the fuel system, electronic compatibility, and so on. For these reasons, drawings for production engines were released, even though test engines were still exhibiting failures. Engineers expected to find solutions and crank necessary changes into the production line. Occasionally, modification kits were dispatched to engines in the field.⁴⁴



VEHICLE EFFECTIVITY			
SA-201 THRU SA-203	SA-204 THRU SA-207 & SA-501 THRU SA-503	SA-208 & SUBSEQUENT; AND SA-504 & SUBSEQUENT	
THRUST (ALTITUDE)	200,000LB	225,000LB	230,000LB
THRUST DURATION	500SEC	500SEC	500SEC
SPECIFIC IMPULSE			
LB-SEC/LB	418MIN	419MIN	421MIN
ENGINE WEIGHT DRY	3,480LB	3,480LB	3,492LB
ENGINE WEIGHT			
BURNOUT	3,609LB	3,609LB	3,621LB
EXIT TO THROAT AREA			
RATIO	27.5 TO 1	27.5 TO 1	27.5 TO 1
PROPELLANTS	LOX&LH ₂	LOX&LH ₂	LOX&LH ₂
MIXTURE RATIO	5.00±2%	5.50±2%	5.50±2%
CONTRACTOR: NAA/ROCKETDYNE			
VEHICLE APPLICATION:			
SAT IB/S-IVB STAGE ONE ENGINE			
SAT V/S-II STAGE FIVE ENGINES			
SAT V/S-IVB STAGE ONE ENGINE			



The J-2 liquid-hydrogen-fueled engine: statistics are presented at top left; at top right, the J-2's injector; above, left, a schematic of the J-2 engine systems; above, Rocketdyne workmen in a "clean room" in the Canoga Park plant are stacking the coolant tubes that will form the wall of a J-2 engine thrust chamber; at left, final assembly of J-2 engines at Canoga Park—J-2s for both the Saturn IB and the Saturn V; below, left, engineers study a J-2 engine that has simulated frigid space conditions; below, right, a cluster of five J-2 engines are readied for firing at Santa Susanna.



STAGES TO SATURN

Various areas of concern in the production of the engine, such as reorganizing the gas generator system sequence to refine the LOX flow and halt burned-out gas generator walls, cropped up along the way. A more serious problem concerned the tendency of the fuel pump to stall. After considerable investigation, researchers isolated the problem as one of excessive gas buildup in the thrust chamber. With the J-2's regenerative full flow mode, a substantial volume of hydrogen gas was created when the first fuel passed through the comparatively warm chamber. The amount of this gas exceeded the rate of flow designed into the injector, and this impeded the rate of flow of fuel downstream in the system while the engine was starting. To solve the problem, the designers developed the prechill sequence for the chamber and pumps alike and established temperature condition limits for the engine before attempting a start. In these and other engine difficulties, Marshall and Rocketdyne applied all the latest analytical methods and computer programs. It still came down to the issue of making an adjustment, however, and then trying it out to see what happened.⁴⁵

Rocketdyne officials hoped to utilize existing engine facilities to test the J-2 engines and components. The unusual characteristics of liquid hydrogen engines generated an excess of problems in the test equipment—valves, transfer lines, and tanks designed for the earlier liquid oxygen technology. To use LH₂ at -253°C, the available equipment had to have its materials rechecked for insulation, sealing, and embrittlement with the new fuel. In 1961, Rocketdyne established a special cryogenic laboratory to devote its attention exclusively to LH₂ paraphernalia. The difficulties extended to numerous items of equipment such as the piping for the LH₂ test-run tanks. A typical test installation included three cryogenic tanks, one with a capacity of 307 000 liters (90 000 gallons) of LH₂ and two smaller tanks each holding 73 000 liters (20 000 gallons) of LOX. The LH₂ tank was a conventional pressure-vessel type, with the addition of a complete vacuum jacket of unusually large design. The liquid hydrogen transfer pipes at the test installation likewise required the vacuum jacket treatment. For years, engineers relied on a double-wall design in transfer pipes that used a bellows in the inside pipe to absorb expansion and contraction. The interior bellows segment presented difficult maintenance problems under normal cryogenic conditions—problems that became pernicious with the introduction of liquid hydrogen. Rocketdyne sought a new approach, and after rejecting a number of candidates, adopted a piping design based on the use of Invar, an alloy pipe with very low expansion characteristics. At the time, the use of Invar piping for such extensive cryogenic operations was the exception to the rule, and the company perforce had to engage in extensive evaluation programs. In its application by Rocketdyne, the use of Invar was "reduced to practice." Invar's virtually negligible thermal contraction permitted long inner pipe runs with no expansion mechanism at all.

UNCONVENTIONAL CRYOGENICS: RL-10 AND J-2

(although the stainless steel outer jacket retained a bellows section for thermal movement). Rocketdyne installed 8-centimeter and 9-centimeter pipe sizes in runs of up to 370 meters and used some welded pipe of up to 25 centimeters in diameter. Technicians also perfected methods for reliable ship welding and field welds of Invar at the test sites.⁴⁶

SUMMARY: RL-10 AND J-2

The differences in thrust and mission requirements gave the RL-10 and J-2 distinctive variations in operating methods and specific details of design. In other ways, there were interesting similarities. In retrospect, the development of the RL-10 and J-2 engines progressed with remarkably few serious hassles. The liquid-hydrogen-fueled engines, just like RP-1-fueled engines, experienced a normal rash of complications and problem phases. It is worth noting that despite the F-1's size and attendant vicissitudes, Rocketdyne was fortunate in having the experience of its H-1 engine development as a base. Although the liquid hydrogen engines were developed and built by two different contractors, the government managed both programs so that information from one program was available to subsequent programs. Lewis Research Center, NASA's facility in Cleveland, represented an interesting intermediary influence, providing a pool of knowledge about liquid hydrogen technology used by Pratt & Whitney and Rocketdyne alike. Just as early work at Lewis was a benefit to Pratt & Whitney's RL-10, Rocketdyne's later J-2 benefited from both Pratt & Whitney and Lewis.

It has been noted that engine development normally preceded development of the stages, and that the engine program often became the pacing item. The Saturn program generally reflected this trend, although at one point it was a stage, not an engine, that threatened to disrupt the tight schedule of Apollo-Saturn.

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IV

Building the Saturn V

It might seem logical to narrate the story of Saturn V's various stages from the bottom up, beginning with the S-IC stage. However, the stages were not built that way. The Saturn V third stage, the S-IVB, evolved first, based on upper stages of the Saturn I and Saturn IB. As the first large unitary Saturn tankage (not a cluster of individual tanks), a rather detailed discussion in chapter 7 of some of the procedures used in S-IV-IVB fabrication and manufacture eliminates repetitious discussion of similar procedures for other stages in succeeding chapters.

The S-IC and S-II stages, while sharing a common diameter, used different propellants. Although S-II contracts were let prior to those of the S-IC, the S-II became the pacing item in the Saturn program, completing its firing tests later than the other components. Chapter 8 explores S-IC and S-II commonalities and contrasts, emphasizing the imbroglio of the S-II program and its eventual recovery.

Computer technology played a consistent role in the evolution of the Saturn vehicles. Chapter 9 surveys computer activity from manufacturing, through stage test, to launch. In flight, the computers of the instrument unit guided and controlled the Saturn V, including the fiery separation of Saturn V stages during their journey into space.

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From the S-IV to the S-IVB

The upper stage of both the Saturn IB and Saturn V evolved from the upper stage of the Saturn I. All three upper stages were manufactured by Douglas Aircraft Company, used liquid hydrogen and liquid oxygen as propellants, and shared the same basic design concepts and manufacturing techniques. The Saturn I upper stage (the S-IV) used a cluster of six engines, but the Saturn IB and Saturn V upper stages (designated the S-IVB for both versions) possessed a larger diameter and mounted a single engine of different design. During one early period of Saturn planning (about 1958–1959), the S-IV was planned as the fourth stage of a vehicle known as the C-4, but the changes and deletions involving the original "C" series left the S-IV in a different role.¹ Instead of entering service as a fourth stage, the S-IV became the second stage of the Saturn I. During late 1959 and early 1960, NASA began plans to name a major contractor for the S-IV stage.

Because the S-IV was the first major Saturn stage hardware to be built under contract, NASA proceeded very carefully. The situation was even more delicate because Wernher von Braun and the Army Ballistic Missile Agency (ABMA) team had not yet been officially transferred from the Army into NASA, although the ABMA group was to be deeply involved in the contractor selection process for the Saturn upper stage.* NASA Headquarters assiduously followed the negotiations.

*Although NASA assumed technical direction of the Saturn program on 18 Nov. 1958, administrative direction was not completely transferred by the Department of Defense until 16 Mar. 1960. On 1 July 1960, the von Braun team was formally transferred to NASA and MSFC began official operations.

STAGES TO SATURN

CONTRACTS FOR THE S-IV

At Huntsville, Alabama, on 6 January 1960, Abraham Hyatt, Deputy Director of Launch Vehicle Programs at NASA Headquarters, met with von Braun, Eberhard Rees (von Braun's technical adviser), and ABMA staff to ensure that S-IV contract procedures met NASA expectations. Hyatt got the ABMA team to loosen up a little on strict constraints that would limit the number of potential applicants; it was agreed that at least 20 companies would get specific invitations to submit proposals. Any other company could request to participate, although Hyatt felt that "most companies will realize that this is a 'big league' competition and I doubt that there will be any companies aside from those selected who would seriously consider submitting a full scale proposal."

During the all-day session at Huntsville, ABMA agreed to set up a technical evaluation team and a business evaluation team to analyze proposals from the various contractors. A source selection board, staffed by ABMA and NASA Headquarters representatives, would then review the findings of the evaluation teams and make a final recommendation to the Administrator. A calendar called for a bidders conference at Huntsville, 26–27 January, contractor proposals submitted 29 February, and source selection board recommendations by 1 April. ABMA was also directed to submit second-stage specifications, a funding plan, and a management plan to Headquarters.²

By the time of the bidders' conference, not all the S-IV specifications had been established. Rather than delay the conference, NASA and ABMA agreed to have bidders submit proposals for a stage to load 54 500 kilograms. Within a month, ABMA promised to determine the precise loading and use this figure in negotiating final details with the winning contractor. Von Braun explained this situation to the first session of the bidders' conference on 26 January. The prospective contractors got an extensive briefing from top NASA and ABMA managers and received a bulky packet of materials to use as guidelines in submitting proposals. The next day was spent answering questions. Following that, the prospective contractors had one month to prepare their detailed proposals; NASA and ABMA had the following month to evaluate them.³ After considering the scope of the project and the guidelines laid down by ABMA, only 11 contractors submitted proposals.⁴

The source selection board made its presentation to NASA Administrator T. Keith Glennan on 19 April 1960. By 26 May, Glennan had reviewed all the relevant materials, and NASA announced that Douglas Aircraft Company had been selected for further discussions leading to a

FROM THE S-IV TO THE S-IVB

final contract for the S-IV stage.⁵ Douglas* and Convair had been the leading contenders, and Glennan finally based his decision on certain subjective factors. The findings of the Source Selection Board tended to give Convair a slight edge in technical competence, although Glennan remarked that "the Douglas proposal, in some ways, seemed more imaginative." Convair, however, scored lower in the business and management areas. No matter who was chosen, Glennan said, minor shortcomings in either the business or the technical areas could be easily corrected. Other reasons, therefore, favored Douglas.

Glennan pointed out that Convair would have a continuing business in liquid hydrogen rockets because of its own Centaur program. Moreover, the Centaur was ticketed for use in proposed Saturn vehicles as an upper stage called the S-V. Glennan apparently had a strong reservation about giving Convair the S-IV stage as well, because "a monopolistic position in this field seems possible." In short, Glennan chose Douglas because "broadening the industrial base in hydrogen technology is in the best national interest."⁶

The choice of Douglas, and the reasons for that choice, stirred a minor controversy. On 12 May, the Committee on Science and Astronautics, House of Representatives, asked the General Accounting Office to investigate NASA's selection of Douglas. The report of the General Accounting Office, dated 22 June 1960, generally sustained Glennan's statements on the matter and noted that his decision "was consistent with the written presentation of the Source Selection Board and other related documents." The report also supported the NASA position on problems concerning logistics and other questions.⁷

During May and June, NASA, Huntsville, and Douglas went ahead with the negotiations that preceded the signing of a final contract. Meeting two or three times a week on the West Coast, conferees hammered out details of costs for planning, tooling, engineering, testing, and manufacturing. A second group worked out details of technical design and engineering and set up continuing working panels that included both government and contractor counterparts. This combination of close collaboration and monitoring by NASA set the pattern for future relationships with Douglas, as well as other stage contractors.⁸ (For details of NASA-contractor relationships, see chapter 9.) During the succeeding months, decisions on engines, configurations, and missions influenced the evolution of the S-IV and led to two versions of its successor, the S-IVB.

*In 1967, Douglas Aircraft Co. and the McDonnell Corp. merged, becoming the McDonnell Douglas Corp., with headquarters in St. Louis, Mo. The former Douglas division in California, responsible for the S-IV and S-IVB, became McDonnell Douglas Astronautics Co. (MDAC). For convenience, the term Douglas is used in the narrative.

STAGES TO SATURN

NUMBERS AND NOMENCLATURE: S-IV AND S-IVB

In August 1960, NASA announced that the S-IV would use a cluster of four Pratt & Whitney rocket engines.⁹ When the development of the Pratt & Whitney LR-119 engines ran into snags, MSFC officials began to lean more and more to the idea of using six less powerful versions. Moreover, the cluster of six engines opened the possibilities of raising the payload capability and promised better inflight control. Finally, the RL-10 type was adopted (see chapter 4). By May 1961, Pratt & Whitney had put together final mockup of the RL-10 and shipped copies to both Douglas and Convair for installation and interface compatibility checks.

On 25 January 1962, NASA Headquarters confirmed the role of MSFC as the lead center to proceed with the two-stage C-1 and to design and develop a three-stage vehicle, the C-5. Mission planners envisioned a series of development flights, testing each stage in successive combinations before a full-dress flight test of the three-stage C-5 vehicles. Eventually, the C-5 would be topped off by an improved S-IV, known as the S-IVB. For this stage, a single J-2 engine would provide the thrust to escape Earth orbit and boost a 44-metric ton payload to the vicinity of the moon.¹⁰ Under this scheme, the S-IVB would have been the last stage to be flight-tested and the "junior member" of the Saturn C-5 vehicle when the big rocket finally lifted off as a complete stack. The reverse happened. The single-engine S-IVB became the real veteran of the Saturn program, active in more launches than any other stage. This was because it became part of an interim Saturn vehicle, between the C-1 and the C-5.¹¹ The new Saturn class vehicle, designated C-1B, relied on a uprated version of the original C-1 first stage but included the S-IVB as the second stage.

NASA acquired the S-IVB under a sole-source procurement contract with the Douglas Aircraft Company. Plans for this variation of the S-IV stage began with an ad hoc working group established at MSFC in August 1961, and NASA Headquarters approved Douglas as the sole-source contractor in December. The space agency seemed somewhat sensitive about the S-IVB contract, because there had been no bidders' conference or active competition by other firms. NASA awarded the contract to Douglas for reasons of cost and schedules: "The similarity of the S-IVB and S-IV stages permits the exploitation of both facilities and technical skills of the contractor now developing the S-IV stage, resulting in substantial savings in both time and money to NASA." In a memo to Associate Administrator Robert Seamans, D. Brainerd Holmes stressed the similarities in configurations which permitted use of the same tooling and materials, as well as facilities for checkout, static testing, and captive firing.¹²

Mission planners at NASA saw a means to accelerate the Apollo program by using the high-energy S-IVB stage of the C-1B to launch manned, Earth-orbital missions with a full-scale Apollo spacecraft. The

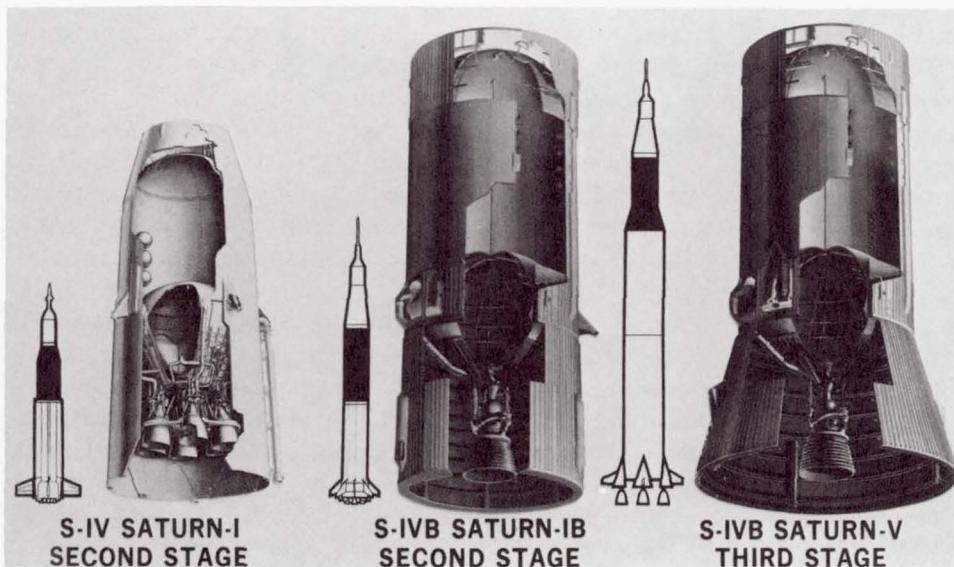
FROM THE S-IV TO THE S-IVB

new vehicle, launched with the instrument unit (IU) segment used on the C-1, also provided opportunities to refine the maneuvers for the lunar missions. The NASA announcement of the C-1B on 11 July 1962 included word that lunar orbit rendezvous (LOR) was the technique chosen for the manned lunar landing missions with the Saturn C-5 launch vehicle. The S-IVB, with its capability for heavier payloads and reignition for translunar injection, was an important element of the LOR scheme. The C-1B offered a fruitful method to try out the critical transposition maneuver, docking of the command and service modules (CSM) and the lunar module (LM), and the translunar sequence of the S-IVB upper stage. During the summer of 1962, Douglas complied with MSFC directives to make the comparatively uncomplicated modifications of the S-IVB to fly on the C-1B vehicle. Early in February 1963, the "C" designation was dropped once and for all. The three Satellites now became the Saturn I, Saturn IB, and Saturn V.¹³

MISSION PROFILE AND DESIGN

Nearly all of the LOX-kerosene boosters in use when the Saturn program began reflected a direct lineage from the ballistic missiles of the 1950s. Although the Thor performed yeoman service for unmanned satellites and probes, and the Atlas and Titan operated successfully through the Mercury and Gemini programs, these boosters had not been designed for such missions. Nor were they capable of orbiting the manned payloads expected in the Saturn program. For these reasons, a unique, staged, large payload-oriented launch vehicle was indicated.

Cutaway drawings compare the S-IV stages on Saturn I, IB, and V.



STAGES TO SATURN

The upper stages of such a vehicle were critical to the eventual success of the mission—especially the top stage, which inserted the payload into the final, stabilized orbit. Douglas engineers were emphatic. “The overall performance of the end-stage has greater influence than the primary stages. The Saturn V launch vehicle for the lunar mission requires 50 pounds [23 kilograms] of booster weight at liftoff for each pound of payload injected into a translunar trajectory,” they explained. “Without high-energy upper stages this factor would be significantly greater.”¹⁴ The key to these high-energy stages was liquid hydrogen as the fuel. An engineer from Douglas, the eventual contractor of the S-IV and the S-IVB, summed up the significance of the decision to use liquid hydrogen. “The combination of hydrogen and oxygen for propellants made the moon shot feasible,” he declared. “Its use in upper stages results in a significant increase in performance over the propellant combinations of oxygen and kerosene then in use in first-stage boosters.”¹⁵

Many aspects of the S-IV design were transferred directly to the S-IVB, even though it mounted only one engine, instead of a cluster of six. The configurations of both upper stages depended on the mission requirement, and ultimately, on the location of the stages in the various Saturn vehicles. Originally, Douglas planned a 5.6-meter-diameter stage for the S-IVB, designed for Earth orbit rendezvous (EOR), requiring a coast in low Earth orbit for as long as 30 days. This permitted time for subsequent launches of other Saturn and Apollo hardware, rendezvous, and preparation for injection into lunar transfer orbit. As the mission profile changed from EOR to LOR, the S-IVB design requirements shifted to a four-day coast period, although the final mission profile called for a four-and-a-half hour coast in low Earth orbit, followed by a translunar injection burn and a two-hour period in translunar coast. Throughout this time of design discussions with MSFC, the proposed stage diameter remained at 5.6 meters, with an interstage to adapt to the 10-meter diameter of the S-II stage of the preliminary C-5 design. Shortly before NASA’s final contract definition of the Saturn V version, Douglas received a design change notice to go from a 5.6-meter version to a 6.6-meter tank. The reason for the change related to the mission of the interim Saturn IB, and the increased diameter allowed added payload capability for launching and testing Apollo components in Earth orbit.

The increased S-IVB capability was also compatible with its ultimate role in Saturn V as envisioned at MSFC. By 1964, the details were fairly well defined and the program manager for the S-IVB, Roy Godfrey, outlined them at a NASA conference in Houston. Briefly, the Saturn V was to place a spacecraft into a translunar trajectory, enable a soft landing on the moon with a manned payload, and return to Earth. In the mission, the S-IVB had two critical responsibilities: get the Apollo craft into orbit, then restart and insert the payload into the translunar trajectory. The

FROM THE S-IV TO THE S-IVB

orbital phase left the S-IVB, instrument unit, and Apollo spacecraft in an Earth orbit of 185 kilometers, where it remained for about four and a half hours, or time for three orbits of the Earth. Following the powered flight, which consumed about half of the propellant, the stage relied on its auxiliary propulsion system during the orbital coast, to ensure proper attitude control and "ullage orientation" of the remaining propellants toward the bottom of the tank prior to engine restart—"ullage" being an old brewmaster's term that referred to the volume of air above a partially full container. After restart, the second burn put the S-IVB and Apollo spacecraft into the translunar trajectory and consumed the remainder of the propellant. With burnout of the S-IVB verified, the transposition maneuver was carried out—a nose-to-nose rendezvous of LM and CSM. Concluding this maneuver, the spent S-IVB and instrument unit were separated from the LM-CSM by retrofire ordnance aboard the S-IVB, and the mission of the Saturn V third stage was over.¹⁶

The nature of the S-IVB mission imposed special requirements on its design. For one thing, the engine and stage needed the capability to restart in orbit. The stage had to have special equipment to ensure storage of propellants and proper orientation while in Earth orbit for four to five hours. The advantages obtained from the mission profile, primarily the coasting orbit and the 185-kilometer altitude outweighed the penalties. At the same NASA conference in Houston in 1964, the head of the Aero-Astrodynamic Laboratory at MSFC, E. D. Geissler, explained the tradeoffs in choosing this particular mission profile.

A "one shot" launch to the moon, as opposed to the LOR mode, had the advantage of permitting a somewhat larger payload. The Earth-orbital sequence carried with it a weight penalty of some 1360 kilograms to supply the S-IVB, IU, LM, and CSM systems with longevity and life support for the extra four to five hours. On the other hand, the "one-shot" launch had to be precisely plotted for liftoff at a fleeting instant of time within a given month. Injection in a direct lunar trajectory could take place only at a time when the Earth and the moon were so aligned that the liftoff point was precisely opposite the moon. The LOR sequence, incorporating a period of coasting, made liftoff much less time-critical. The time of departure from Earth orbit was also less critical, since the "launch window" in Earth orbit lasted about four hours and recurred twice daily. Moreover, the extra time in Earth orbit permitted more accurate tracking of the vehicle and allowed the mission controllers to plot a far more accurate start of the "burn" for insertion into the lunar transit trajectory. The Earth-orbital coast path of 185 kilometers represented some compromises. Although higher orbits would have reduced aerodynamic heating, the orbit chosen allowed better tracking and telemetry.¹⁷

Other considerations affecting the design of the S-IVB and its predecessor, the S-IV, involved the propellants. The physical characteris-

STAGES TO SATURN

tics of liquid hydrogen altered the apparent logic of tank location. The weight of the propellants included 87 200 kilograms of LOX and 18 000 kilograms of LH₂ (with some variations, depending on mission requirements). Logically, the layman might assume that the smaller LH₂ tank should be placed on top of the LOX tank, as was done with the RP-1 fuel and LOX in the S-IC first stage. The volume of the lighter LH₂ was much greater, however, requiring a larger vessel to hold 252 750 liters (69 500 gallons), as compared with only 73 280 liters (20 150 gallons) of LOX. If designers placed the LH₂ tank in the aft position, with the LOX tank above, LOX feed lines would be longer and would have to be run through the interior of the LH₂ tank (with additional problems of insulating the LOX lines from the colder liquid hydrogen). Longer LOX lines would have to be mounted externally between the LOX tank and the engines. Either solution carried a high weight penalty for long lines and associated hardware. It made more sense to put the fuel tank containing the LH₂ in the forward location, making it easier to route the LH₂ feed lines internally around the smaller and more compact oxidizer tank.¹⁸

One further difference characterized the S-IV and S-IVB in comparison to the only other significant rocket stage that burned liquid hydrogen, the Centaur. The Centaur, like the Atlas, relied on internal pressure for rigidity and stiffness of the tank walls. With no pressure, the Centaur would buckle and collapse. The Saturn S-IV and S-IVB, like other stages, evolved as self-supporting structures that gave added confidence in the man-rating requirements. Furthermore, the various stresses placed on the oversized stages during erection and transportation to the launch pad, as well as the time-consuming checkout and countdown, were more tolerable.¹⁹ The S-IV and S-IVB structures owed much to an earlier Douglas rocket, the Thor.

Although the S-IV relied on six RL-10 liquid hydrogen engines and the S-IVB mounted only one J-2, the choice of propellants remained the same. The S-IVB carried more propellant for a longer time, and the mission of the Saturn V, calling for restart in orbit, imposed some new design requirements. Stage interfaces in different Saturn vehicles required different skirt and interstage designs.²⁰ The stages, however, were essentially the same. The delivery of the first S-IVB flight stage to NASA in 1965 was the culmination of a single thread of the story of the design, fabrication, and manufacture of the S-IV and S-IVB liquid hydrogen upper stages.

FABRICATION AND MANUFACTURING

The transfer of Thor experience to the more advanced S-IV and S-IVB began with the tank skins and carried into many related fabrica-

FROM THE S-IV TO THE S-IVB

tion and production techniques, including metal removal by machining and by chemical milling, forming by stretching and bending, welding, chemical bonding, and mechanical fastening.

When the Thor project entered the phase of design studies in the mid-1950s, engineers screened a number of metallurgical candidates for the rocket's propellant tanks. With its heritage of advanced aircraft design and production, Douglas had considerable expertise in handling various aluminum alloys. These metals and other nominees were therefore subjected to extensive test and analysis for use as cryogenic tankage. Adaptability for fabrication and inspection requirements for quality assurance were included in the tests. The Thor tanks not only had to be amenable to cryogenics with the liquid oxygen, but the tanks also had to be weldable. Welded joints promised the only sure way to control leaks of the cryogenic fuels—cryogenic leaks had a high potential of explosion. As it turned out, the 2014 alloy selected for the Thor worked so well that Douglas chose it for the S-IV and continued its use on the S-IVB.²¹

During the Thor design program, engineers considered several fabrication methods for the tanks, including conventional skin and stringer designs, as well as a monocoque style derived from aircraft construction. Both were rejected because of drawbacks of weight and construction requirements. With a design goal for very thin but rigid walls, Douglas finally settled on an integrally stiffened shell structure, using special equipment to literally "carve out" ribs from the inside walls of the tank. The wafflelike pattern that resulted was both practical and efficient. The waffle recesses were about 7.5 centimeters square, bounded by ribs that increased the buckling strength of the tank walls.

The S-IV and S-IVB featured the same waffle-shaped integral stiffening for their liquid hydrogen tanks, although designers increased the waffle size, and the S-IV skins were milled from 1.3-centimeter plates, as compared with 1.9-centimeter plates used for the S-IVB. To produce the seven separate segments for the S-IVB liquid hydrogen tank, Douglas used a Giddings and Lewis mill with a 3.6×12.2 -meter bed and two router heads. Depending on particular requirements for some of the more complex areas and special sections for the later attachment of accessories, machining for each segment consumed 106 to 134 hours. In the waffle-machined form, the tank segments were formed to the proper curvature. To prevent the waffle ribs from buckling, Douglas personnel inserted reusable polyethylene blocks, then ran each segment through a Verson press for progressive forming. The Verson power brake, originally used in the production of various panels for the DC-8 jet aircraft, was unique in size for its time. Rated at 25 300 000 grams per square centimeter (3 600 000 pounds per square inch), it could handle sheet stock up to 1.9 centimeters thick and 13.4 meters long and form the sheets to specification with an automatic program for feed and contour.²²

STAGES TO SATURN

The components for the S-IVB originated from several California locations. The liquid hydrogen tank segments were formed on the Verson press at Long Beach. The preliminary milling took place at the Douglas facility in Santa Monica, which also fabricated and assembled all propellant tank domes and bulkheads, and completed the subassembly of the liquid oxygen tank. Final manufacturing of S-IVB stages took place in the new Douglas complex at Huntington Beach, begun in January 1963 specifically for S-IVB production. The Huntington Beach facility featured a distinctive architectural detail—external bracing on the production and assembly buildings—that enhanced cleanliness on the inside because there were no interior beams, supports, or braces to gather dust and dirt that might contaminate components during final assembly. Douglas funded the construction of the Huntington Beach facility out of its own capital reserves, and made it one of the most advanced aerospace plants of its kind in the United States. As for the other major stage contractors, Boeing operated out of the converted Michoud facility owned by the government, and North American used a mixed facility at Seal Beach. Executive and administrative offices owned by North American Rockwell were across the street from assembly and checkout areas that were leased from NASA.²³

DOMES AND BULKHEADS

The designers of the domes for the S-IV and S-IVB settled on a true hemispherical shape. This design meant the domes were deeper and increased the overall weight of the stage (in contrast to the elliptical domes of the S-II stage). Douglas accepted this penalty in exchange for the extra strength inherent in the design, the possibility of a smaller diameter for the stage, and the resulting simplicity in tooling. The domes were composed of nine triangular segments, or gores, that were stretch-formed over special dies to accurate contours. With multiple contours, the requirements for partial waffle structuring of the gore segments could not be met by the mechanical milling. Instead, Douglas used chemical milling for this task, with masked segments dunked in large vats of chemicals for carefully calculated periods of time to remove certain areas of the aft LOX dome to a specified depth. Workers next moved the separate gore segments to a special meridian welding jig for the automatic welding sequence (under a plastic tent for cleanliness) that joined together the various segments of the aft and forward domes.

Technicians at Santa Monica performed the demanding job of welding the segments of the common bulkhead and propellant tank domes. The triangular segments, which look like pieces of orange peel, were placed into a welding jig for what appeared to be a very simple operation. Not so. "We cut our eye teeth on this phase of manufac-

FROM THE S-IV TO THE S-IVB

ing," recalled H. E. Bauer, a company executive who was deeply involved in the S-IV and IVB project. To join the metal "peels" together to form a hemispheric half-shell, Douglas used a rotating fixture and a "down hand" technique of welding. In this mode, the weld torch moved on a track while the molten welding "puddle" remained in the proper position from force of gravity, which also minimized undesirable porosity. While welding the orange peel segments, a strange problem developed. The tracking system for the weld torch hinged on the detection of discontinuities produced by induced eddy currents along the seams to be welded. The exasperating torch heads wandered all over the place, however, apparently unable to follow the seams at all. Oddly enough, the trouble was traced to manufacturing standards being set too high! "Because the individual segments had been so carefully formed and sized," Bauer explained, "upon butting them together no sensible level of electrical discontinuity to the instrument developed." Some insensitive soul suggested the application of a bastard file to rough up the seams and create enough discontinuity that the tracking system could do its job. After adamant protests from the manufacturing people at Long Beach, Douglas specialists refined the tracking system to give it a much higher gain, and scarfed (grooved) the segments to provide a path for the tracking sensors to follow.²⁴

Like Centaur, the S-IV and S-IVB relied on a common bulkhead to separate the fuel from the oxidizer. In more conventional designs, the propellants were housed in separate tanks, each with its own forward and aft domes and tank walls. This required an intertank assembly to join the tanks rigidly together as a complete vehicle, making for greater length and greater weight. The common bulkhead, in the case of the Douglas upper stages, meant a reduction in structural weight of up to 20 percent. Douglas developed a double-faced hemispherical structure, about five centimeters thick, with a pair of 2014-T6 aluminum shells on either side of a fiberglass honeycomb core. The bulkhead separated LH₂ at -253°C (-423°F) on one side from LOX at -172°C (-297°F) on the other side. The common bulkhead served as an end dome for both LH₂ and LOX tanks, as well as insulation to prevent heat flow from the LOX to the colder LH₂. Otherwise, the liquid oxygen would freeze solid. The bulkhead was designed to take the thermal stresses and reverse pressures, as well as to survive a major loss of pressure from either side. Douglas designer and engineer Ted Smith emphasized that the design of the common bulkhead originated with Douglas, independent from MSFC. Originally conceived for the S-IV, the bulkhead was adapted to the second-generation S-IVB with only minor changes for larger diameter and attachment.²⁵

The curved, concave aluminum shells were quite thin: 0.813 millimeters for the forward sheet and 1.4 millimeters for the aft sheet, with a 6.63-meter diameter for the S-IVB. Working with such large

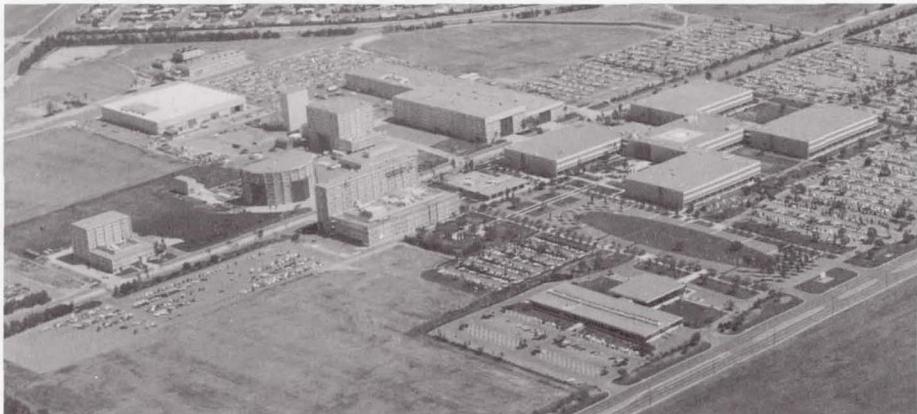
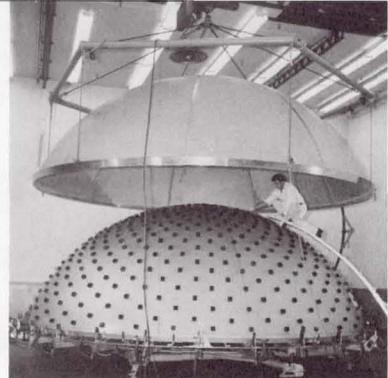
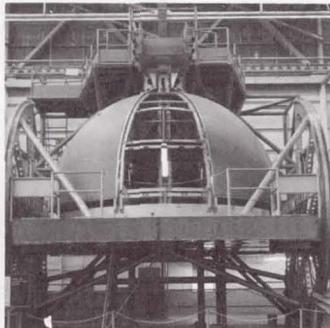
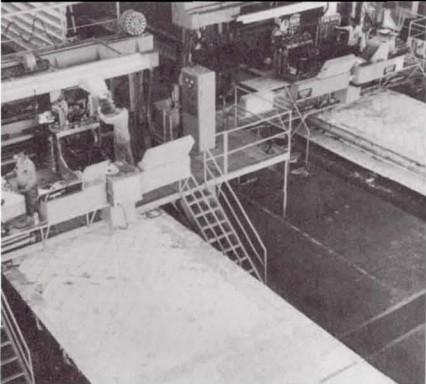
STAGES TO SATURN

diameter, thin-skinned sheets required exacting procedures. The complete aft dome sheet was set up on a bonding fixture to which the honeycomb was bonded. The forward dome sheet was moved into position over the fixture and bonded into place atop the honeycomb filler, completing the three-layer "sandwich" construction. This construction was, at least, the ideal the engineers hoped for. In practice, the milling and bonding of the forward dome sheet created a serious problem. The sheet's contours differed from the honeycomb layer underneath, and the aluminum skin developed an exasperatingly uneven terrain of gaps, gullies, and wrinkles.²⁶ Douglas finally contrived a method of measuring the valleys and hills between the honeycomb and the forward sheet, then sculpting the honeycomb's contours for an acceptable fit. The technique was known as the "Paleno block system," involving a meticulous, tedious process done almost entirely by hand.

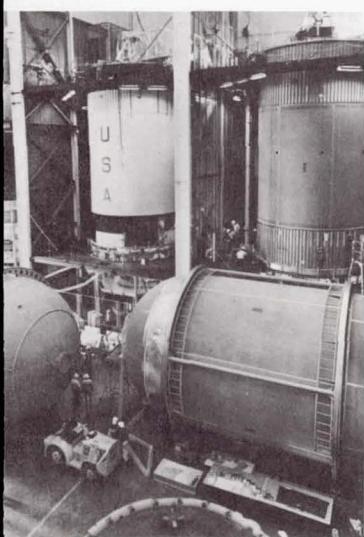
The procedure began with the top of the aft dome exposed before the honeycomb insulation was affixed and bonded. Workers then set up 350 small honeycomb blocks over the entire surface. Each block carried a pad of putty, encased in cellophane, on its top. With the putty-pad Paleno blocks in place, the forward dome sheet was lowered to approximate its final installation, making contact with each of the putty pads. The dome was hoisted up and workers measured the indentation on each pad to plot the variations in the aft dome's contours. Next the blocks were removed and the production honeycomb sections were fitted and bonded to the aft dome sheet. With templates in place to indicate the positions of the Paleno blocks, the honeycomb surface was "spot faced" to the Paleno measurements, which provided reference points for the next operation: sanding the entire surface by hand to the desired contours for a custom fit. In a wry understatement, engineers from Douglas and MSFC agreed: "This hand-sanding operation is time-consuming and subject to some human error." After cleaning, workers spread adhesive over the surface, and the entire common bulkhead unit went through the final bonding cycle at 182°C (360°F) inside an oversized autoclave. Finally, the unit was machined to the required tolerances on a Niles boring mill, which also machined the circumferential attach rings to mate the common bulkhead to the aft liquid oxygen dome.²⁷

PUTTING TOGETHER THE PIECES

For the aluminum structural assemblies of the S-IVB, Douglas relied on conventional designs, fabrication, and manufacturing developed from its experience as an airframe manufacturer. Details of the assemblies for the forward skirt, aft skirt, interstage, and thrust structure were produced by numerically controlled equipment, with panels riveted together in automatic machines. The forward and aft skirts included fittings to



Top left, S-IVB tank skins, the basic structural walls of this rocket stage, are milled on the inside in a wafflelike pattern to reduce weight while retaining most of the structural strength. Top center, the dome of the tank is being fitted with gores before welding. Top right, the two dome sections of the S-IVB's common bulkhead are being precisely fitted before insulation is applied between them. Above, the Douglas Airplane Co. facility at Huntington Beach, California, is fabricating and assembling the S-IVB stages. At left are major structural components of the S-IVB; at upper left is a complete hydrogen-oxygen tank; in the right foreground a straight-sided Saturn IB interstage is flanked by a pair of aft skirts, with a forward skirt to the rear. Below, left, shows production in full swing: in towers at right and center, stages are being checked before shipment to Sacramento for firing tests; in the left tower, a tank section is being cleaned before insulation is applied; in lower right, a tank is being given its final interior work and the completed tank at left is about to be hoisted into the tower from which the photos were taken. Below, right, the intricate job of applying insulation to the interior of the liquid hydrogen tank proceeds, as another individually numbered insulation tile comes off the conveyor belt.



STAGES TO SATURN

support assorted electrical and mechanical subsystems and vents, as well as propellant lines and umbilical connections required for operations at the launch site. The aft skirt carried the auxiliary propulsion system modules and the aft interstage contained fittings for the retrorockets. The thrust structure featured skin and stringer construction for strength and rigidity. It contained several access panels and carried attach angles for miscellaneous engine fittings and other equipment. The bottom of the thrust structure carried the fitting for the engine mount and was machined on a numerically controlled vertical turret lathe and a five-axis milling machine.

Inside the labyrinth of the Vehicle Tower Complex at Huntington Beach, the fabricated components of the S-IVB finally reached the nexus of their journey, and emerged as a complete rocket stage. The Vehicle Tower Complex reminded the observer of the Vehicle Assembly Building at Cape Kennedy. Although smaller in size, the complex had the same immensity of scale. It was a single building, 36 meters high, enclosing a total of 2230 square meters. The interior had provisions for six large bays, each capable of holding a complete S-IVB vehicle, with two overhead cranes (10.1 and 20.2 metric tons) to swing the stages to the required station. Basically, the bays were internal compartments to house a series of assembly towers, with movable work platforms at various levels in each. The complex included a pair of assembly and welding towers, a tower for hydrostatic testing, another for cleaning and degreasing, and a final pair of checkout towers. To control and monitor the activities of each tower, an elaborate vehicle checkout control room adjoined the complex.

The assembly of the complete vehicle in one of the assembly and welding towers involved the joining of the complete LOX tank and LH₂ cylinder. The steps to accomplish the task were complex, requiring both inside and outside welding, with the stage in upright, as well as inverted, positions. The tank assembly techniques relied on many special maneuvers, including the mating of the LH₂ tank cylinder and the LOX tank. With the LOX tank in position at the bottom of the assembly tower and the LH₂ cylinder hanging overhead, workmen heated the base of the LH₂ tank cylinder, expanding it slightly. Then the heated cylinder was slipped down over the LOX tank, creating a close "interference fit." When cool, the LH₂ cylinder and LOX tank presented a minimum gap for welding and enhanced the prospects of a high-quality weld with minimum distortion. The joining of the LH₂ forward dome and tank cylinder (with the assembly inverted) required special care to ensure precise vertical alignment. Douglas relied on a special support fixture at the top of the assembly to bring the dome and cylinder together. Automatic controls using beams of light verified alignment between the top and bottom of the assembly.²⁸

During these final sequences, careful x-ray tests and a penetrant dye

FROM THE S-IV TO THE S-IVB

check were performed to search for invisible structural inconsistencies, ending with verification of the structural integrity of the complete LH₂-LOX tank assembly. Using the overhead cranes, Douglas personnel moved the completed S-IVB tankage assembly to the hydrostatic test tower for a hydrostatic test to a proof pressure five percent over the design load limit. Like the other manufacturing and test operations, the hydrostatic test was strictly programmed and regulated. Douglas set up a very elaborate sequence to load the water, with redundant automatic controls and extensive instrumentation. The complicated sequence did not always work. During one check, the tank became overpressurized and was damaged. There were long conferences to decide on a revised system to eliminate the inadvertent overpressurization.

Curiously, the satisfactory solution came not from more sophisticated instrumentation, but by an elementary approach to the problem. "After a lengthy analysis, it was decided to use a system so old and basic that it had almost been forgotten," mused H. E. Bauer. "A standpipe—one that extended beyond the roof so that the tank could not be overpressurized, since the system would spill the excess water overboard." So a new space-age structure reared above the flat Pacific coastline at Huntington Beach in the form of an open water standpipe 43 meters high, equipped with beacons to warn passing aircraft, and rigged with a wire cage to discourage nesting birds.

Birds presented a problem in more ways than one. At Huntington Beach, workmen complained of misanthropic pigeons roosting and hovering around the rafters of the high-ceiling production buildings. The droppings not only created sanitation problems for the Saturn stages, but also for the workers. A hand-picked pigeon elimination section went to work on the problem. High-frequency whistles worked for a time, but the pigeons returned. Occasional indoor potshots at the ubiquitous birds produced humanitarian protests and holes in the roof. Workmen tried to pigeon-proof the building by sealing off all outside openings, but the persistent creatures fluttered in through gaps where the huge door machinery and track rails were installed. Ornithologists consulted on the problem finally suggested some specially treated seeds to affect temporarily the pigeons' nervous systems. It worked. After pecking at the seeds, the pigeons sat quite still for a time, then finally flew off, never to return. Cheerfully, the maintenance crews refreshed the seed supply every 60 days just to make sure their feathered foes kept their distance.

Back in one of the assembly towers, the S-IVB's related structural assemblies (forward skirt, aft skirt, interstage, and thrust structure) were mated to the tankage. The last stop was one of the checkout towers, where the J-2 engine was installed, and technicians concluded the last installations and checkout of the vehicle. Aboard a special dolly, the S-IVB rolled back to the main assembly building for painting. Finally,

STAGES TO SATURN

technicians established the stage's total empty weight, center of gravity, and moment of inertia. Then the S-IVB was ready for shipment.²⁹

LH₂ TANK INSULATION: DESIGN FACTORS

The odyssey of the S-IVB third stage through the Vehicle Tower Complex included one major interruption—the installation in a nearby building of the liquid hydrogen tank's internal insulation. This special installation process required a considerable amount of individual fitting by hand, and the search for the proper insulation materials absorbed many months of time and effort. The story of LH₂ insulation for the S-IV and IVB typifies many of the unexpected development problems that cropped up during the Saturn program, and illustrates the considerable amount of tedious handwork that went into sophisticated Saturn rockets.

At the start of the S-IV program in 1960, the decision to use liquid hydrogen in the upper tank presented designers with a formidable insulation problem. The LH₂ tank was designed to hold 229 000 liters (63 000 gallons) of LH₂, filling 296 cubic meters and weighing 17 000 kilograms. Prior to the Saturn program, LH₂ had been used mainly in small quantities in laboratories. Imperative questions emerged about its qualities when used in comparatively larger volume. Efficient insulation on this massive scale had many unknowns, and engineers at Douglas consistently recalled the insulation problem as a significant aspect in the evolution of the S-IV stage.³⁰ One facet of the insulation story involved the composition of the insulating material, and a second related to its location—internal or external?

Some of the preliminary studies at Huntsville envisioned the use of insulation in a dual role on the upper stage of the Saturn. Because the stage would have long periods in orbit, designers considered using external insulation as a means of protection from meteorites that could pierce the walls of the liquid hydrogen tank and perhaps touch off an explosion. The combination insulation-covering-and-meteorite shield would be jettisoned before the upper stage made its second burn for the translunar injection that would carry it out of the most hazardous meteorite zone.³¹ Nevertheless, to the engineers who opted for internally mounted insulation, this alternative to exterior application made very good sense. The insulation selection process also reflects several intriguing elements of the problems of designing, building, testing, and flying large rockets in space missions.

Very early in the program, internal insulation seemed more and more advantageous to many Douglas engineers, even though more was known about external types. Only one other aerospace firm in the country could claim any experience in the field of liquid hydrogen

FROM THE S-IV TO THE S-IVB

propellants, and so Douglas personnel, accompanied by some NASA representatives, made a trip to San Diego to the Convair Division of General Dynamics Corporation. The Centaur design used exterior insulation, and the people at Douglas wanted to see it. Following several conferences and exchanges of ideas with Convair, the Douglas team became more and more intrigued with the possibilities of internal, as opposed to external, mounting of insulation. Part of the reason for this decision stemmed from Convair's trials and tribulations with the external mode and concurrent reservations on the part of NASA's Lewis Research Center in Cleveland, Ohio. For these reasons—and a number of specific design factors—Douglas put the insulation on the inside.³²

In the case of the S-IV, the basic philosophy emphasized simplicity and the utilization of expertise already in hand from previous missile and space vehicle experience. Douglas engineers reasoned that, first, very little was known about the effect of large volumes of cryogenic fluids on metals and, second, even less was known about insulation materials. Pursuing the goal of simplicity, the designers separated the problem of insulation from the problem of tankage structure. This separation enabled design experimentation in the uncharted field of insulation materials to proceed in one direction without forcing changes in metal structure configuration, which proceeded in a parallel line at the same time. This method also avoided the time-consuming threat of a totally new design approach such as double-walled tanks to combine both insulation and structural factors. With insulation materials being nonstructural, the search for a desirable insulation design had a wider range of possibilities.

The mission configuration itself influenced the insulation factor. Because the mission for which the S-IV was designed did not include an extended coast phase, materials with a wide range of thermal conductivity for a brief operational period could be included in the list of potential candidates. Structural design of the S-IV stage also enhanced the potential efficiency of internal insulation. The fiberglass and honeycomb construction of the common bulkhead yielded a very high insulation factor in separation of the cold LOX and the colder LH₂. Further internal insulation on the upper LH₂ segment of the bulkhead would help reduce the tendency to solidify the warmer LOX on the other side.³³

As engineers began to think more and more of the design factors in S-IV construction and operation, internal insulation seemed even more attractive in terms of thermal stress qualities. Thermal stress was extremely critical in the filling of the rocket's fuel tanks when LH₂ at -253°C (-423°F) came into contact with tank walls at warmer ambient air temperatures. If insulation was external, it was feared that the LH₂ would create severe thermal stress and potential damage to the tank walls as it was pumped in, because the aluminum walls possessed a very high coefficient of expansion. Even if no serious weakening was caused by the

STAGES TO SATURN

first filling, repeated operations could create problems, especially for vehicles undergoing a series of static tests and tankage checks. Internal installation of the S-IV's insulation would obviously eliminate many such problems in the tank walls. During filling, internal insulation promised dramatic advantages in reducing LH₂ loss through boil-off. When external insulation was used, nearly 100 percent of the tank's capacity had to boil off to bring the temperature of the walls down to -253°C (-423°F) to keep the LH₂ stable. Given the volume of tankage of the S-IV, external insulation meant a need for much greater quantities of expensive propellants and additional paraphernalia to provide a venting system to cope with the furious boil-off. By using internal thermal insulation, on the other hand, it was possible to expect only 25 percent boil-off of the tank's capacity, reducing the mechanical complications and all the other inherent drawbacks. Even with the highly efficient insulation finally developed for the S-IV and S-IVB, an LH₂ tank topped off at 100 percent capacity before launch needed constant replenishment, since the boil-off required compensation at rates up to 1100 liters (300 gallons) per minute.

Even with the tank finally filled, the design team foresaw additional problems with external insulation. If it became damaged and the metal underneath was exposed, that extremely cold area would tend to pull air into the damaged section. The air would liquefy and freeze, making a larger cryogenic surface, which would attract even more air, liquefaction, and icing. The whole process threatened to create an unacceptable situation of thermal losses around the damaged area, thermal instability, and a hazardous problem during ground operations.

The repeated fill-and-drain operations associated with testing and boil-off conditions raised the requirements not only for insulation materials, but also for adhesives. When Douglas began its catalog of materials and alternative modes of installation, no satisfactory adhesives could be found to bond external insulation to the outside walls of a tank filled with cryogenic fuel. On the inside, however, where the fuel made contact with insulation and not metal, the insulation created a warmer bond line where it touched the interior wall surface. In this more congenial environment, available adhesives would work. Even the plans for the test-firing operations of the S-IV program presented special problems to be solved. Because of the S-IV's volume of LH₂ fuels, a new system had to be devised to store large quantities of liquid hydrogen for repeated test firings and to transfer it to the stages set up in the test stand.³⁴

The process of frequently repeated testing and acceptance checks, as well as final loading prior to launch, encouraged Douglas engineers to shift toward internal insulation as a means of minimizing potential damage to the insulation from normal external handling. For example, external insulation seemed susceptible to degradation during the han-

FROM THE S-IV TO THE S-IVB

dling and transportation of the vehicle through the test and checkout phase, to say nothing of the degradation and cracking to be expected from atmospheric exposure as the rocket stage moved through these procedures and into the long transportation phase from California to the Cape for launch. Testing programs indicated that interior mounting yielded extra margins of reliability even if an accidental break in the insulation materials occurred. The cryogenic liquid coming into contact with the warmer tank wall became gaseous, and itself acted as insulation against further contact, thus reducing the thermodynamic loss.³⁵ After weighing the alternatives, internal insulation was confidently chosen for the S-IV stage.

LH₂ TANK INSULATION: MATERIALS

Meanwhile, the search for an effective insulation material continued. At one point, balsa wood was a leading candidate. Balsa had all the primary characteristics for good insulation: lightness, ease of shaping, and insulative capacity. But there was a question of adequate supply of the right kind of balsa. Each S-IV liquid hydrogen tank was 5.5 meters in diameter and 10 meters long. S-IVB tanks were 6.7 meters in diameter and 12.2 meters long. Obviously, a considerable amount of balsa would be required during production, and no one was completely sure that current stocks of balsa would suffice. A special task force analyzed the available data and reluctantly reported that the combined harvests of the balsa forests all over South America fell short. Even as the data were being analyzed, balsa was losing its allure. Lab testing revealed internal wood flaws and other deficiencies that made it less and less desirable as insulation. Still, the balsalike qualities of lightness, insulative characteristics, and ease of shaping were goals of the Douglas engineers in their quest for the perfect material, available in quantity. As Ted Smith put it, "We set out to manufacture synthetic balsa."³⁶

After conducting tests of a number of potential materials, Douglas technicians finally devised their own insulation. To form workable masses of insulation material, they contrived a three-dimensional matrix of fiberglass threads, woven onto a boxlike form reminiscent of a child's weaving frame—top to bottom as well as back and forth. After it was strung, the matrix frame was placed in a mold, and polyurethane foam was poured in and cured. The result was a reinforced foam block, 30 centimeters square and 20 centimeters deep, which could be sawed into a pile of flat plaques, then machined to the required convex and concave contours appropriate for the interior of the S-IV liquid hydrogen tank. The recessed waffle pattern construction of the tank's interior required special attention in shaping each tile to fit. Using a machine tool with custom fixtures and cutters, operators recessed edges and cut steps on

STAGES TO SATURN

each tile. The tiles then slipped into the appropriate indentation in the waffle pattern and still covered the notched step cut of each adjoining tile for a smooth surface. The waffle pattern included some variations in design, requiring each of the 4300 tiles to be numbered and individually shaped to its unique position inside the tank.³⁷ In cutting the tiles, Douglas discovered a true case of serendipity—the saw cuts left small ends of the fiberglass threads sticking out around the edges, which served admirably to engage the adhesive as each tile was installed.³⁸

An insulation facility provided an environmentally controlled work area during the installation process. Technicians with protective gloves and shoe covers entered the tank through an opening in the forward section, then began laying tile in the aft area near the common bulkhead, working their way back to the entry point. The numbered tiles, attached to a conveyor belt, were coated with adhesive by an automatic applicator set up in an adjoining room, then traveled via the conveyor into the tank to be affixed “by the numbers.”

During this procedure, the installation facility’s environmental control equipment maintained the tank’s interior temperature at 13°C to 18°C (55°F to 65°F) to extend the adhesive’s effective life. Once a section had been completely tiled, workers applied a special fiberglass cloth liner, then retired while a vacuum bag pressed the tile further into the waffle recesses and the tank temperature rose to 43°C (110°F) to set the adhesive. Machinery then rolled the tank around its axis to a new position, and another installation cycle began. Final steps in the operation included application of a fiberglass cloth (impregnated with resin) as a sealant over the insulation tiles, another curing period, and a concluding cure cycle at 71°C (160°F) for 24 hours. Using mounts that remained exposed above the insulation, fitters completed installation of valves, helium bottles, and other hardware before a last cleaning cycle in the degreasing tower. After the sensitive fuel-level probes were inserted, technicians sealed off the fuel tank at the top with a big, circular piece of tank skin aptly called the “dollar hatch.”³⁹

Throughout the Saturn program, an observer could count on the recurrence of a familiar refrain—use as much existing technology as possible—as design studies for a new stage or phase of the program began. When internal insulation was first developed for the S-IV, it was designed for a flight duration of no more than 10 minutes. With the acceptance of the LOR mode for the manned Apollo mission, the S-IVB, as the third stage, had a planned flight time of up to 4.5 hours, with enough LH₂ propellant for the second burn for translunar injection. This fact presented an obvious question: could an insulation technique for a 10-minute mission serve as well for a mission lasting 4.5 hours? Would designers and engineers have to repeat the process of selection and fabrication of a new insulation material? Fortunately, engineers and technicians found that the LH₂ insulation as originally developed for the

FROM THE S-IV TO THE S-IVB

S-IV could be easily adapted to the S-IVB. The LH₂ tanks of the S-IVB were designed large enough to compensate for the anticipated boil-off losses in flight, and only minor changes were required in fabricating internal insulation for the newer third stage.⁴⁰

OPERATION: THE S-IVB PROPULSION SYSTEM

Many of the systems required for effective stage operation of the S-IVB were similar to the more conventional LOX-RP-1 operations. The introduction of liquid hydrogen necessitated some new techniques, however, and the differences in upper stages introduced additional design variations. The ubiquitous S-IVB upper stage, sharing the J-2 powerplant with the S-II stage, exemplified the nature of stage systems required for Saturn vehicle missions, particularly the Saturn V. Saturn V's S-IVB included six basic systems: propulsion, flight control, electrical power, instrumentation and telemetry, environmental control, and ordnance.

Effective operation of the J-2 engine depended on the ability of S-IVB to manage the supply of liquid oxygen and liquid hydrogen on board. The propulsion system included not only the J-2 engine but also the propellant supply system, a pneumatic control system, and a propellant utilization system (PU system). The LOX propellant tank could take 72 700 liters (20 000 gallons) of liquid oxygen, loaded after a preliminary purge and prechill cycle. For launch, the tank was filled in four separate phases, calculated to accommodate the interaction of cryogenic propellants with the tank walls and associated equipment. The slow fill sequence, at 1800 liters per minute (500 gallons per minute), raised the propellant volume to 5 percent capacity, and the fast fill sequence, at 3600 liters per minute (1000 gallons per minute), continued to 98 percent of the tank's capacity. The tank was topped off at 0 to 1100 liters per minute (0 to 300 gallons per minute) and replenished as required at 0 to 110 liters per minute (0 to 30 gallons per minute) until launch. A single fill-and-drain line could fulfill all requirements and disconnect automatically at the time of launch. The fuel tank of the S-IVB carried 229 000 liters (63 000 gallons) of liquid hydrogen. Like the LOX tank, the LH₂ tank required purge, chilldown, and fill in four stages: slow fill, fast fill, slow fill to capacity, and replenish. Its fill and drain connection also automatically disconnected at liftoff.⁴¹

The pressurization of each propellant tank during the boost and restart phases not only enhanced propellant feed to the engine, but also helped the stage withstand bending moments and other flight loads. When Douglas designed the Thor, shortages in helium supply forced the company to use nitrogen for pressurizing the tanks. However, the appeal of helium's greater volumetric characteristics when heated, and its later

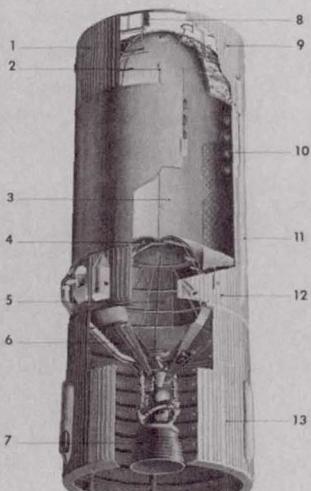
STAGES TO SATURN

availability, led to its use in Saturn upper stages. Before liftoff, both S-IVB tanks relied on helium pressurization from ground sources; thereafter, an onboard supply was used. To expand the cold helium carried in nine storage bottles, the helium was heated either by an engine heat exchanger, or by a piece of specially designed Douglas equipment, the O₂H₂ burner, which drew oxidizer and fuel directly from the vehicle's LOX and LH₂ tanks. For additional pressurization, the liquid hydrogen tank also used gaseous hydrogen, tapped directly from the J-2 during steady-state operation. The system for tank pressurization and represurization employed sophisticated techniques and minimum weight. Particularly notable were the special helium storage bottles, made of titanium and charged to about 211 kilograms per square centimeter at -245°C (3000 pounds per square inch at -410°F), and the O₂H₂ helium heater. The latter was a unique item on the S-IVB; Douglas personnel remembered that early designs produced a lot of ice and clogged up. Essentially a simple concept, the heater required a considerable effort to qualify it for the man-rated Saturn.⁴²

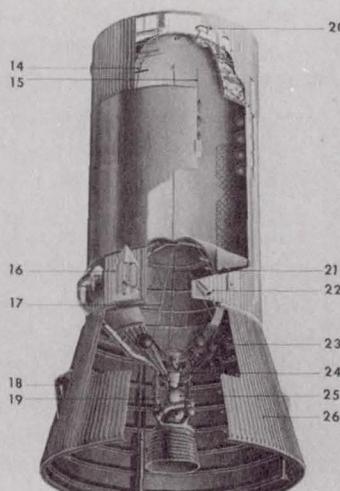
The fully loaded LOX tank was kept pressurized with gaseous helium 2.7–2.9 kilograms per square centimeter adiabatic (38–41 pounds per square inch adiabatic), maintained through launch, boost phase, and the start of stage-engine operation. The inflight helium supply came from the nine helium bottles submerged in the liquid hydrogen tank. During engine operation, a special engine heat exchanger expanded the helium before it was fed into the LOX tank, maintaining required pressures. During the orbital coast phase, pressure decayed in the LOX tank. Because there was no extraneous ground source to supply helium and because the engine heat exchanger to expand the helium was not effective until steady-state operation of the engine, an alternative repressurization source was required. This was the function served by the O₂H₂ burner. It was located on the thrust structure and looked very much like a miniature rocket. It did, in fact, have an adjustable exhaust nozzle and generated 71 to 89 newtons (16 to 20 pounds) of thrust, expelled through the stage's center of gravity. To repressurize before the second burn, the O₂H₂ burner operated to expand a flow of helium from the nine helium storage spheres. This repressurized the LOX tank. After ignition, the engine heat exchanger once more provided the mechanism for the flow of expanded helium gas.⁴³

For the LH₂ tank, initial pressurization came from an external helium source to stabilize tank pressures at 2.2–2.4 kilograms per square centimeter adiabatic (31–34 pounds per square inch adiabatic). When this operational level was reached, the boil-off of LH₂ inside the tank was enough to maintain pressure during liftoff and boost, until the J-2 engine started up. At this point, the fuel propellant pressurization system relied on gaseous hydrogen bled directly from the engine system. During orbital coast, the fuel tank pressure was maintained by LH₂ boil-off, with

S-IVB STAGE



SATURN IB

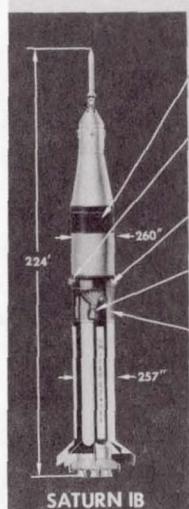


SATURN V

- | | | | |
|----------------------------|--------------------------------------|---------------------------------|------------------------------|
| 1. FORWARD SKIRT STRUCTURE | 8. ELECTRICAL MODULE PANEL | 15. PRESSURIZATION LINE | 22. ULLAGE ROCKET |
| 2. P.U. PROBE (HYDROGEN) | 9. ANTENNA-RANGE SAFETY | 16. APS MODULE | 23. AMBIENT HELIUM SPHERES |
| 3. HYDROGEN TANK | 10. COLD HELIUM SPHERES | 17. INSTRUMENTATION PROBE (LOX) | 24. LOX FEED LINE |
| 4. ANTI-SLOSH BAFFLE | 11. TUNNEL | 18. RETRO ROCKET | 25. ENGINE RESTART SPHERE |
| 5. LOX TANK | 12. LOWER UMBILICAL PANEL | 19. HYDROGEN FEED LINE | 26. AFT INTERSTAGE STRUCTURE |
| 6. THRUST STRUCTURE | 13. AFT INTERSTAGE | 20. HYDROGEN VENT | |
| 7. J-2 ENGINE | 14. INSTRUMENTATION PROBE (HYDROGEN) | 21. P.U. PROBE (LOX) | |

S-IVB DIFFERENCES

SATURN IB VS SATURN V



FORWARD SKIRT
SATURN IB 150 LBS LIGHTER - LIGHTER PAYLOAD

**AUXILIARY PROPULSION AND
ULLAGE SYSTEM**

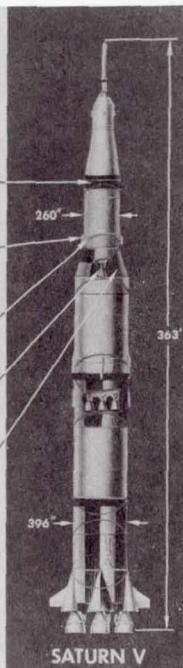
SATURN IB 40 LBS LIGHTER - ATTITUDE CONTROL
AND VENTING REQUIREMENT LESS ON SATURN IB
THAN ON SATURN V.

AFT SKIRT
SATURN IB 500 LBS LIGHTER - LIGHTER PAYLOAD

PROPELLION SYSTEM
SATURN IB 1500 LBS LIGHTER - LESS HELIUM STORAGE
REQUIRED. ENGINE WILL NOT BE RESTARTED IN ORBIT.

INTERSTAGE
SATURN IB 1300 LBS LIGHTER - 260 INCH DIAMETER.
SATURN V FLARED FROM 260" DIA. TO 396" DIA.

NOTE WEIGHT DIFFERENCES BASED ON CURRENT
ESTIMATES OF OPERATIONAL STAGES.



STAGES TO SATURN

a special vent-relief system to avoid overpressures. Additional excess pressure was used in a continuous "propulsive vent system," which helped keep the propellants settled toward the bottom of the tank. Like the LOX tank repressurization sequence, the fuel tank repressurization sequence for the second burn relied on the O₂H₂ burner, which repressurized the LH₂ tank simultaneously with the LOX tank. Once the J-2 engine reached steady-state operation, LH₂ pressures reverted back to gaseous hydrogen bled from the engine.⁴⁴

The J-2 engine created one unique problem for the S-IVB stage: the "chilldown" cycle prior to engine start. As part of the propellant system, the S-IVB stage included the chilldown sequence to induce cryogenic temperatures in the LOX feed system and J-2 LOX turbopump assembly before both the first J-2 burn and the restart operation in orbit. This process enhanced reliable engine operation and avoided the unwelcome prospect of pump cavitation, which might have caused the engine to run dangerously rough. On command from the instrument unit, a LOX bypass valve opened and an electrical centrifugal pump, mounted in the LOX tank, began to circulate the oxidizer through the feed lines, the turbopump assembly, and back into the main LOX tank. This chilldown sequence began before liftoff and continued through to boost phase, right up to the time of J-2 ignition. The equipment operated again during orbital coast, anticipating the second burn of the J-2 for the translunar trajectory, and a concurrent sequence ensured proper chilldown for the LH₂ feed lines and turbopump assembly. The S-II second stage used a similar operation.⁴⁵

PROPELLION: PROPELLANT UTILIZATION SUBSYSTEM

With two kinds of propellants aboard a liquid-propelled rocket, designers wanted both tanks to run dry at the same time so as not to compromise mission performance. Residual amounts left in either of the tanks would subtract from the accuracy and stability of a desired trajectory or orbit. As a mechanism for propellant management, Saturn liquid hydrogen stages relied on the propellant utilization system. Developed for the S-IV, the PU system was used in both versions of the S-IVB, as well as the S-II second stage. Its primary function was simple: "to assure simultaneous depletion of propellants by controlling the LOX flow rate of the J-2 engine." With a PU probe located in both the LOX and LH₂ tanks during propellant loading operations, the system also provided information about the propellant mass accumulating aboard the stage.

Prior to the development of the S-IV, ballistic missiles that used kerosene and LOX propellants incorporated an "open loop" propellant utilization. PU rates were analytically determined on the basis of the powerplant, payload, and mission profile and were confirmed after many

flight tests. Operational vehicles were then loaded with propellants to meet calculated goals for varying missions and targets; small errors were acceptable. This approach was simply not satisfactory for the S-IV. In the first place, high costs ruled out a long series of test flights to establish an accurate utilization curve. In the second place, the use of LH₂ presented too many variables in loading operations and during orbital coast missions. It was estimated that the stage could end up with 1360 kilograms of residual propellants in an open-loop configuration—a serious weight penalty for an Apollo-Saturn mission. So the S-IV design team decided on a “closed loop” PU system to regulate the propellants in flight and thus to ensure the positive depletion of both tanks. The PU system would continuously sense the amount of propellant in each tank and regulate the engine mixture ratio to come as close as possible to simultaneous depletion.

The decision to use a capacitance sensor followed an exhaustive examination of alternative liquid gauges. Although capacitance gauges were familiar in industrial and aircraft operations, the S-IV was the first to use it in the PU system for rocket vehicles. The cryogenic propellants posed a number of problems that led designers almost inexorably to a capacitance gauge. Sensors to indicate fluid levels could not take into account the variations in the tank geometry. Furthermore, standard sensors simply could not cope with sloshing during flight and “boiling” effects that constantly altered the liquid-level line. Designers also discarded the possibility of density sensors at the bottom of the propellant tanks, because the density of cryogenics was apt to vary from one point to another inside the same tank. The PU capacitance probe, an original Douglas design, was intended to overcome these problems through the use of a “gauging system which measured mass by integrating a fluid property related to density over the length of the tank.” The PU capacitance probe could literally “read” the dielectric constant of the propellants in the tanks.

Despite its accuracy, the PU system was primarily used for loading and monitoring propellants in flight. Operational missions continued to rely on a highly refined “open loop” technique.⁴⁶

A computer program suggested a number of PU probe designs, and a series of tests confirmed the eventual configuration. From the outside, the probe looked very much like a thick pipe, with length determined by its location in the LOX or LH₂ tanks of the S-IV, S-IVB, or S-II. An outer aluminum electrode fitted over an inner stainless electrode. The LOX tank probe was installed through the bottom, and the LH₂ probe was installed through the “manhole” opening at the top. During liftoff and boost phase, the ullage movement yielded very accurate readings, which continued through engine operation. In the case of the S-IVB, observers closely watched the mass reading at engine cutoff, and calculated LH₂ boil-off rate during orbital coast. During preignition ullage for the S-IVB

STAGES TO SATURN

stage of the Saturn V, monitors got a new reading to confirm their earlier calculations, preparing for engine start and the translunar trajectory burn.⁴⁷

The PU probe reported the propellant mass as a continuous volume and height relationship in the tank. Because the probe's accuracy was directly related to the accuracy of the volume in the respective propellant tank, each tank required individual calibration for each stage. The huge tanks all exhibited variations as a result of the one-at-a-time fabrication process, and further variations in dimensions occurred with cryogenic propellants on board. Technicians, therefore, subjected the propellant tanks of each stage to a precise water calibration and converted the results to cryogenic values later.

The last element of the propulsion system consisted of the pneumatic control system. Except for pneumatic valves on the J-2 engine, the S-IVB gaseous helium pneumatic control system operated pneumatic valves, such as the LOX and LH₂ vent relief valves, fill-and-drain valves, and chilldown valves. The helium supply came from spheres mounted on the thrust structure.⁴⁸

OTHER S-IVB SYSTEMS

The flight control system gave the S-IVB stage its attitude control and thrust vector steering from correction signals originating in the instrument unit. The vehicle was steered by hydraulic actuator assemblies that gimbaled the J-2 engine. The hydraulic equipment included both electric and engine-driven pumps, as well as an auxiliary pump. The design of the hydraulic actuators owed much to the insistence of engineers at MSFC. When Douglas began design work on the S-IV actuators, the company developed a unit that was slim and long, very similar to the actuators that Douglas had perfected for landing gear in airplanes. The Huntsville design group, relying on their past experience with the Redstone and other rockets, argued that thrust levels and mission environment of the S-IV called for shorter, thicker actuators. Sure enough, the Douglas actuators developed some unacceptable instabilities. The company finally subcontracted the work to Moog Industries, who built the actuators to MSFC specifications.

The actuators played an important role in addition to thrust vector control. To prevent damage to the engine during liftoff, boost, and stage separation, the instrument unit commanded the actuators to keep the engine in the null position and repeated this function prior to the reignition sequence. For thrust vector control in the pitch and yaw directions, two actuators gimbaled the engine as required. Roll control during powered flight was provided by the auxiliary propulsion system (APS). During orbital and translunar coast periods, this system provided

FROM THE S-IV TO THE S-IVB

attitude control in all three axes (roll, pitch, and yaw). During coast, attitude was controlled by the APS. The two APS modules, mounted 180° apart on the aft skirt assembly, each contained four small engines: three for roll, pitch, and yaw; and one for ullage control.⁴⁹

Although the stage was completely programmed for automatic operation, ground observers monitored its operation from start to finish via the telemetry and instrumentation system. The stage carried one transmitter, using two antennas. During staging, some of the data were lost in transmission, and similar losses occurred during parts of the low Earth orbit. To acquire as much information as possible during each mission, the S-IVB carried a digital data acquisition system that recorded sample data pertaining to stage operation, then played it back when in range of ground stations. The telemetry and other electrical equipment was kept from overheating by the environmental control system. The system used temperature-controlled air in the aft skirt and interstage during countdown and coolant fluid in the forward skirt, circulated from equipment during countdown and flight. Before liftoff, the environmental control system also purged the aft skirt and interstage and the forward skirt with gaseous nitrogen, which cleared them of combustible gases accumulated during propellant loading and storage. Before liftoff, the S-IVB systems used external power. In flight, the stage relied on a clutch of silver-oxide-and-zinc batteries. Two 28-volt DC batteries were located in the forward skirt. The aft skirt carried one 28-volt DC battery and one 56-volt DC battery, as well as the auxiliary hydraulic pump. The S-IVB ordnance system included the mechanism for stage separation, ignition of the retrorockets mounted on the interstage, operation of the ullage engines, and range safety devices to destroy the stage in flight if necessary.⁵⁰

A RATIONALE FOR GROUND TESTS

No Saturn launch vehicle was ever lost during a flight mission. The phenomenal success of the Saturn program probably owed most to two basic philosophies: (1) the stringent reliability and quality assurance programs during manufacture, and (2) exhaustive ground testing. Emil Hellebrand, of MSFC's Science and Engineering Laboratory, stressed the significance and economy of comprehensive testing at a meeting of the NASA Science and Technology Advisory Committee in Houston in June 1964. At that time, the Saturn I had completed six flights, including two launches with the S-IV second stage and its advanced liquid hydrogen engines. Aside from a minimum of problems, the 100-percent record of success vindicated the thoroughness of the drawn-out testing program, and Hellebrand advocated similar stringent programs for the succeeding generations of Saturn vehicles. "Money spent on well planned and

STAGES TO SATURN

properly evaluated ground tests is very worthwhile and is only a tiny fraction of the money lost in flight failures," he reminded his listeners.⁵¹

Each stage required its own testing program, tailored to the mission objectives and characteristics of the stage itself. Overall, the test phase of the Saturn program accounted for as much as 50 percent of the total effort, in terms of allotted man-hours and physical resources. This high figure reflected the intensity of the effort to reduce the risks inherent in the manned Apollo-Saturn program. In general, the respective Saturn stages progressed through three major test phases: ground test, static firing, and demonstration flight test. In the case of the S-IV and S-IVB, five different test configurations of the stage verified the manufacturing sequences as well as the overall design. A "structural test cylinder" was produced to check the ability of the tankage to take compressive forces of loading and storing cryogenic propellants. A "facilities stage" allowed other contractors and MSFC to work out interface problems, as did mating and launch facilities at Kennedy Space Center (KSC). An "all-systems stage" permitted tests of the general compatibility of vehicle equipment, pneumatic control systems, and other features. The "dynamic test stage" afforded engineers the opportunity to determine vibration characteristics during the launch and mission trajectory. The static-test-firing stage, or "battleship" stage constructed of heavy gauge stainless steel, allowed earliest possible test firing to verify major components of the propulsion systems and engines and to identify design changes required to improve performance and reliability. Because these various test items were more often than not undergoing simultaneous test and evaluation, MSFC and the contractors had to work carefully to ensure integration of design changes before committing themselves to production of the flight-stage configuration.

The earlier battleship phase allowed propulsion tests to run independently of the schedule for flight-weight structures, and gave engineers the chance to begin tests of the propulsion systems as much as 9 to 12 months earlier than anticipated. The steel sinews of the battleship articles also yielded a strength factor and safety margins that allowed installation of some components before their rigorous qualification. For the second phase of static firing, engineers introduced actual flight hardware—the "all systems" test.⁵²

These static tests for Douglas stages took place at the company's own Sacramento Test Operations (SACTO). The company made significant progress in automated checkout and countdown (see chapter 13), and in the handling and storage of the quantities of cryogenics required for S-IV and IVB tests. One of the ticklish problems of working with large rocket stages filled with liquid hydrogen concerned the danger of hydrogen leaks. As one authority on rocket fuel wrote, "All sorts of precautions have to be taken to make sure that oxygen doesn't get into

FROM THE S-IV TO THE S-IVB

the stuff, freeze, and produce a murderously touchy explosive." There was an added, perverse character about leaks that produced hydrogen fires—in daylight, the flame was invisible. It was possible to inadvertently blunder into the searing flame. As Harold Felix, who managed SACTO operations in the late 1960s, put it, "You don't want to go into a countdown of firing if you got leaks. It is a good way to blow up stages." But how to detect an invisible fire? Douglas used infrared TV cameras, but they still did not provide visibility at every angle. Just to make certain, SACTO had a special examination crew, outfitted with protective clothing and equipped with brooms. The men "walked down" the stage, from the top scaffolding to the bottom, extending their brooms ahead of them. If the broom suddenly sprouted into flame, the men knew they had discovered a hydrogen leak. Still, accidents could happen, even when extra precaution was taken.⁵³

Because the SA-5 launch, scheduled in January 1964, was intended to use both the S-I and S-IV stages live, the S-IV all-systems vehicle was given extra scrutiny and analysis. In a countdown for the test firing of an S-IV all-systems vehicle at SACTO on 24 January 1964, the vehicle exploded and burned. Once before, large quantities of LOX-LH₂ propellants had exploded, but that had been at several thousand meters during the first Centaur launch, and the incident had not lent itself to close observation and evaluation. So the incident at SACTO was carefully scrutinized. W. R. Lucas and J. B. Gayle, both of MSFC, headed the investigating team of 11 members from Douglas and NASA. They traced the cause to an overpressurized LOX tank. At the time of the accident, tape records showed the pressure to be considerably above the design limits of the S-IV tank. Watching films taken during the test sequence, the investigators spotted a rupture in the peripheral area of the common bulkhead, and the nearly instantaneous flash of the explosion. The LH₂ tank in all probability was ruptured within milliseconds of the LOX tank break. Previously, engineers had possessed no real data on the TNT equivalent of LOX-LH₂ explosions. The examination by the Lucas and Gayle team had special significance for its acquisition of hard data, useful in future design of test sites and installations for maximum safety.⁵⁴

In spite of the test accident, NASA officials decided to go ahead with the launch of SA-5 on 29 January 1964. Because the recent S-IV test stage explosion was caused by inadvertent overpressure of the LOX tank, mission planners conjectured that the SA-5 launch could reasonably proceed, with special attention to LOX tank pressures during countdown at Cape Kennedy. The launch and subsequent Saturn I launches were successful.

As the Saturn IB and S-IVB also got under way, Douglas began fabrication of the first flight version in September 1964. In addition to changes in some of the electronics systems, the basic evolution of the

STAGES TO SATURN

S-IVB from the second stage of the Saturn IB to the third stage of the Saturn V involved interface requirements with the larger diameter of the Saturn V second stage and the controls to ensure the restart of the J-2 engine for the translunar trajectory burn. The S-IVB third stage profited heavily from S-IVB second-stage battleship tests. The tests went well—with one catastrophic exception. Just as the S-IV test program experienced the loss of a complete stage, the S-IVB test program also lost a stage. This time it was a flight stage, S-IVB-503.

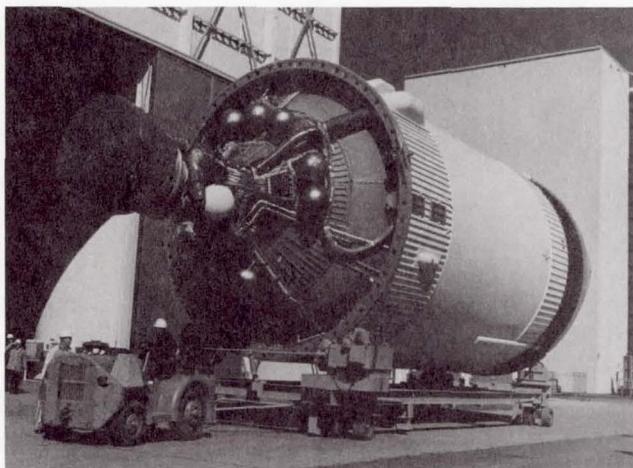
With the S-IVB-503 in position at Test Stand Beta III at SACTO, the Saturn V's third stage was scheduled for acceptance testing on 20 January 1967. The terminal countdown went perfectly, but about 150 seconds into the simulated mission, and prior to stage ignition, the stage countdown was aborted because of a faulty computer tape mechanism. The Douglas crew successfully corrected the computer difficulty, recycled the test, and began again. With the terminal countdown once more unwinding, all systems reported normal. Eleven seconds before the simulated liftoff occurred, however, the stage abruptly exploded in a fiery blast of smoke and debris. Most of the stage was blown completely out and away from the test stand, with only jagged shards of metal left hanging. Adjacent service structures lost roofs and windows, and the nearby Beta II stand was so severely damaged that it was shut down. Within three days of the incident, another special investigation team convened at SACTO to analyze the probable cause.

The group finally traced the source of the explosion to one of the eight ambient-temperature helium storage spheres located on the thrust structure of the J-2 engine. The exploding sphere ruptured the propellant fill lines, allowing liquid oxygen and liquid hydrogen to mix and ignite, setting off an explosion that wrecked the stage. Further analysis showed that the sphere had been welded with pure titanium weld material, rather than the alloy material specified. The helium sphere and the weld seam had been previously tested to withstand extremely high overpressures, but repeated tests on the sphere prior to the acceptance firing sequence had created the weakness that ultimately resulted in disintegration of the sphere and destruction of the stage. With this information in hand, Douglas and NASA personnel agreed on revised welding specifications and quality control for the helium spheres. Replacement spheres were built in-house at Douglas from then on.⁵⁵

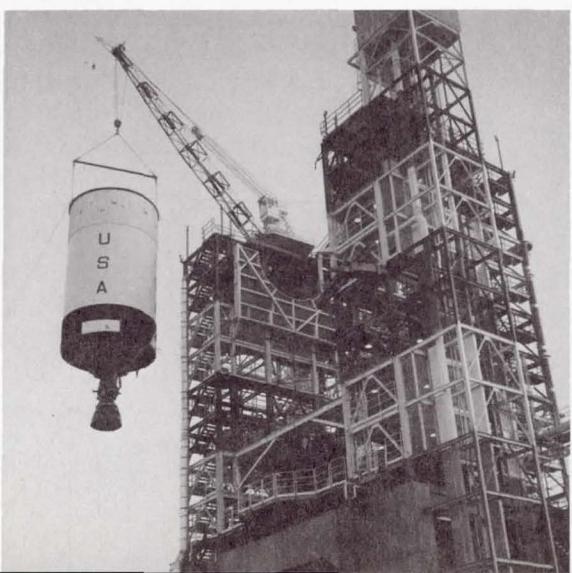
The loss of S-IVB-503 illustrated the ever-present probability of human error. More stringent procedures on the production line could help avert such problems, and NASA planners also hoped to achieve high reliability in launch operations through the use of fully automated checkout, countdown, and launch. With the introduction of automated checkout, at least the final moments before launch were completely insulated from human foibles. Developed in parallel with the production of the first flight stages of the S-IVB, automatic checkout was inaugu-

FROM THE S-IV TO THE S-IVB

rated with the full-duration acceptance test firing of the S-IVB flight stage for launch vehicle AS-201 (the two-stage Saturn IB). At SACTO on 8 August 1965, a Douglas news release announced the milestone: "The full-duration acceptance test firing of the first S-IVB flight stage marked the first time that a fully automatic system was used to perform the complete checkout, propellant loading and static firing of a space vehicle." The burn of the S-IVB-201 stage lasted 452 seconds, and the automatic checkout equipment not only manipulated the static firing but also performed all the intricate operations for initial checkout of the stage at Huntington Beach, as well as the postfiring checkout at SACTO.⁵⁶ The static test of S-IVB-201 was a test of men as well as machines. All the Douglas personnel were keenly anxious to have a successful demonstration of both the flight stage and the checkout equipment, and the end of the test uncapped many weeks of keyed-up emotions. A group of gleeful technicians began tossing their cohorts into the waters of a nearby pond and, in an exuberant finale, included a waitress from one of the cafeterias, along with an unsuspecting sales representative who happened to be visiting the SACTO facility.⁵⁷



Above, a new S-IVB stage rolls out of the production facility, on its way to firing test. The white sphere is the combination helium-hydrogen start tank for the J-2 engine; the other tanks contain helium for pressurization. Right, an S-IVB stage is hoisted into the Beta test stand in Sacramento for the acceptance firing test.



STAGES TO SATURN

The static tests were by far the most dramatic element of the Saturn V test program. They were also some of the most expensive. The cost of static firing the S-IVB alone came to \$3.2 million for each stage. Keeping a close watch on the funding from his vantage point in Washington, Apollo Program Director, Major General Sam Phillips, questioned MSFC about continuing this expensive practice. In his reply, Brigadier General Edmund F. O'Connor, Marshall's Director of Industrial Operations, reminded Phillips that the incentive and performance clauses in existing contracts with stage manufacturers would be so expensive to renegotiate and rewrite that early savings simply would not accrue if the static-firing requirement was ended. Also, cryogenic calibration occurred during the static test operations, and these expensive calibration operations, using a full load of cryogenic propellants, would have to be done in any case. O'Connor pointed out that static tests and postfire checkout frequently exposed shortcomings that might have caused the loss of the mission. Even during propellant loading, problems cropped up. Elimination of static firing would mean that vehicle hardware got its first exposure to full cryogenic loads while the vehicle sat on the pad, only hours away from ignition and liftoff—not a propitious time to discover a leaky hose or faulty valve. O'Connor won his point. For the time being, static firing continued.⁵⁸

SUMMARY: CENTAUR, S-IV, AND S-IVB

In the evolution of the hydrogen-fueled S-IV and S-IVB, Douglas drafted its designs against the mission profile and general requirements established by the Marshall Space Flight Center. Douglas engineers were not always happy with the close technical monitoring from Huntsville, a strong characteristic of the Marshall team. Differences were inevitable, given the pride and confidence of personnel on both the contractor's side and the customer's side. In retrospect, Douglas personnel emphasized their role in pushing ahead in many technical areas, apart from contributions by their counterparts in MSFC's well-equipped laboratories. Douglas people also emphasized their independence from Convair in the development and production of liquid-hydrogen-fueled upper stages, though Douglas did learn from Convair's experience. Contractor research carried out under the aegis of NASA was not proprietary; under NASA cognizance, Douglas and Convair held a number of technical discussions. The resident MSFC representative at Douglas, O. S. Tyson, accompanied Douglas personnel during such exchanges, including excursions to static-firing test sites.⁵⁹

Because both the Centaur and the S-IV carried the same RL-10 engine, a strong tendency to follow Centaur's general design concepts persisted. Earl Wilson, one of the design engineers at Douglas, said that

FROM THE S-IV TO THE S-IVB

he had to fight hard to keep the Douglas S-IV from looking like another Centaur. Nevertheless, Wilson affirmed the cooperation of Convair and especially appreciated the collaboration of Pratt & Whitney technical representatives in establishing the different RL-10 format for the S-IV stage.⁶⁰

Ted Smith, another leading Douglas engineer, was less willing to acknowledge a debt to Centaur. Douglas gained no substantial design factors from Convair, he explained, primarily because the S-IV stage was a much larger and more complex rocket system. The Centaur was closer to the missile experience of its creator, Convair, and also to its immediate predecessor, the Atlas. Atlas and Centaur parallels were evident in the thin-skinned, pressurized-tank concept, as well as the basic philosophy of the design of the common bulkhead in each. At Douglas, the S-IV design absorbed the propellants, engine system, and even the common bulkhead concept, but the Centaur and S-IV structures had marked differences. The S-IV was much more akin to Douglas's earlier experience with the Thor vehicle in terms of structural design materials and fabrication of the tankage. Moreover, the Centaur was a comparatively small vehicle. The S-IV was rather large, for its time, and the tankage concept was extrapolated from the Thor development.⁶¹ Even though the Centaur also featured a common bulkhead separating LH₂ and LOX within the same tankage structure, Hal Bauer noted the different S-IV honeycomb design. This feature relied on prior Douglas applications in aircraft wing panels and some phases of earlier missile design, although the extent of the honeycomb installation in a concave form was unique for its time, Bauer pointed out.

The size of the original S-IV was significant but largely overshadowed in light of subsequent evolution of the Saturn V stages, the S-IC and the S-II. It should be remembered that the Saturn I and Saturn IB, with the S-I and S-IB first stages respectively, relied on the somewhat makeshift design approach of clustered tanks to supply the requisite volume of propellant. The S-IV tankage was unique. Nothing that size had previously been attempted for any American rocket, and the liquid hydrogen fuel created unique design challenges. In many respects, then, the S-IV emerged as the first really definitive rocket stage of the Saturn program. It did not begin with a feasibility study; it was not a case of joining together existing tankage components and proven engines. The S-IV evolved as a result of requirements established by a comparatively elaborate mission profile, an untried engine design and exotic propellant combination, and unusual size. Its success, so early in the program, was a notable achievement of the manned space program and a credit to NASA, MSFC, Pratt & Whitney, and Douglas Aircraft Company.

The special significance of the S-IV extended very quickly into the heart of the Apollo program. As noted earlier, the upper stage of the Saturn V played the final, truly critical role of the Saturn vehicle's job:

STAGES TO SATURN

Earth orbit of the vital payload; then, a second burn for the translunar trajectory. This was the role of the eventual Saturn V third stage, the S-IVB, whose technology sprang from the recent technological past. "Just as Thor technology led us to the S-IV," Hal Bauer wrote, "the S-IV led to the S-IVB." The technological knowledge and development experience came from the half-dozen S-IV stages of the Saturn I program. The S-IV and S-IVB possessed the same basic design fundamentals, including internal insulation, the forward and aft domes, and the common bulkhead. S-IVB manager, Roy Godfrey, also underscored the experience with the S-IV that established high NASA confidence in its successor. "Of prime importance has been the opportunity to observe and analyze the performance of the S-IV stage," Godfrey stated, "which formed the foundation upon which the S-IVB detailed design was built."

In comparing the S-IV to the S-IVB, there was a strong consensus among those who worked on both that the 'more advanced' S-IVB was, nevertheless, simpler. The earlier upper stage, with its cluster of six engines, created more design tangles than the single-engine S-IVB, even though the latter had to have the capability to restart in space. Some of the instrumentation for the S-IVB was more sophisticated, but aside from the engine, there were no major differences between the two. The electronics, including the circuitry and design for the propellant utilization probe, for example, passed easily from the S-IV to the S-IVB.⁶²

This fortunate evolutionary advantage was not the case in other Saturn V stages. The S-IC first stage and the S-II second stage shared a common diameter, but there the resemblance stopped. They were built by different contractors, used different propellant systems, and had different mission requirements and development histories.

The Lower Stages: S-IC and S-II

The lower stages for the Saturn I and Saturn IB, designed and built for Earth-orbital operations, traced their ancestry back to the Juno V. Saturn I and IB technology was characterized by the "bargain basement" approach—off-the-shelf tankage, and available engines. Saturn V, a vehicle designed for lunar voyages, required new engineering concepts. Designers for the S-IC and S-II stages tried to follow NASA's general guidelines to use proven technology in the big new boosters, avoiding problems and delays. Nonetheless, problems abounded.

In the first place, there was the problem of proportions. The S-IC and S-II both were sized to a 10-meter diameter. In the fabrication of booster tankage, new tooling of unique size and capabilities had to be built, and fabrication of the tank cylinders and domes required circumferential welds and meridian welds of unprecedented length. For manned flights, the welds also had to pass stringent inspection to "man-rate" the Saturn V vehicle. The difficulties faced by welding engineers and technicians were formidable. In terms of the nearly perfect welds required for the man-rated stages, weld passes of several dozen centimeters were considered possible (though highly difficult) within the state of the art; now, requirements for the S-IC and S-II demanded nearly perfect welds of several dozen meters. The task became a maddening cycle of "cut-and-try" operations. The long welding runs generated unmanageable distortions in large-circumference cylinders. Additional difficulties included coping with the varying thickness of pieces being joined by the welding pass; quality requirements for the integrity of welded seams and alignments of the components created still more revisions to operational manuals. Experienced welders had to be taught the new techniques through on-the-job instructional classes conducted on-site by the contractor.

STAGES TO SATURN

The problem of size confronted both major contractors for the Saturn V lower booster stages, Boeing being contracted for the S-IC, and North American* for the S-II. Although the S-II contract preceded that of the S-IC, the Boeing effort got off to a faster start largely because of the unusual role played by the Marshall Space Flight Center in the early stages of design and fabrication, and the availability of existing facilities at MSFC's Huntsville complex and at Michoud. The S-II encountered more than its share of problems, for a variety of reasons. Use of LH₂ propellants in a stage of this size was unique. There were insulation problems, materials and fabrication problems, and, in the opinion of MSFC, management problems. The difficulties were overcome, but not without casualties.

THE S-IC AND THE HUNTSVILLE CONNECTION

When the contract to build the biggest stage of the Saturn V, the S-IC first stage, was awarded to Boeing on 15 December 1961, general outlines of the first-stage booster were already fairly well delineated. The main configuration of the S-IC had already been established by MSFC, including the decision to use RP-1, as opposed to the LH₂ fuel used in the upper stages. Although LH₂ promised greater power, some quick figuring indicated that it would not work for the first stage booster. Liquid hydrogen was only one half as dense as kerosene. This density ratio indicated that, for the necessary propellant, an LH₂ tank design would require a far larger tank volume than required for RP-1. The size would create unacceptable penalties in tank weight and aerodynamic design. So, RP-1 became the fuel. In addition, because both the fuel and oxidant were relatively dense, engineers chose a separate, rather than integral, container configuration with a common bulkhead. The leading issue prior to the contract awards related to the number of engines the first stage would mount.¹

The C-5 configuration, late in 1960, was generally portrayed as a rocket with four F-1 engines in the first stage. Not everyone was happy with this approach, particularly Milton Rosen at NASA, recently tagged by Brainerd Holmes as the new Director of Launch Vehicles and Propulsion in the Office of Manned Space Flight. At the direction of Holmes, Rosen organized a special committee to hammer out conclusions and configurations on launch vehicles (see chapter 3). The group moved into a block of motel rooms in Huntsville for an intensive two-week stint, including, as Rosen recalled, one marathon stretch of five days of almost

*North American Aviation merged with Rockwell Standard in 1967, becoming North American Rockwell (NAR), and later, Rockwell International. For convenience, the term North American is used in the narrative.

THE LOWER STAGES: S-IC AND S-II

around-the-clock negotiating. Among other things, the committee's report, delivered to Holmes on 20 March 1961, recommended five, not four, engines in the first stage.

Rosen apparently took the lead in pressing for the fifth engine, consistent with his obstinate push for a "big rocket." The MSFC contingent during the meetings included William Mrazek, Hans Maus, and James Bramlet. Rosen argued long and hard with Mrazek, until Mrazek bought the idea, carried the argument to his colleagues, and together they ultimately swayed von Braun. Adding the extra power plant really did not call for extensive design changes; this was Rosen's most convincing argument. Marshall engineers had drawn up the first stage to mount the original four engines at the ends of two heavy crossbeams at the base of the rocket. The innate conservatism of the von Braun design team was fortunate here, because the crossbeams were much heavier than required. Their inherent strength meant no real problems in mounting the fifth powerplant at the junction of the crossbeams, and the Saturn thus gained the added thrust to handle the increasingly heavy payloads of the later Apollo missions. "Conservative design," Rosen declared, "saved Apollo."²

At second glance, MSFC people themselves found no good reason not to add the extra engine, especially with the payload creeping upward all the time. "I had an awfully uneasy feeling, you know," von Braun remembered; "every time we talked to the Houston people, the damn LEM [lunar excursion module] had gotten heavier again." The added F-1 also relieved some of the concern about accumulating exhaust gases, with explosive potential, in the large space between the original four engines, and helped solve a base-heating problem in much the same way. The physical presence and exhaust plume of engine number five filled the void and directed gases and heat away from the base of the first stage. At a Management Council Meeting on 21 December 1961, NASA formalized the five-engine configuration for the S-IC.³

In the past the Army Ballistic Missile Agency (ABMA) had performed its own preliminary design work—and even fabrication—on the first stage of launch vehicles. At Marshall the designers approached the S-IC somewhat differently. They enlisted Boeing's cooperation at a much earlier stage of the game, giving increased responsibility to the contractor. After signing the contract in December 1961, Boeing engineers worked "elbow-to-elbow" with MSFC in finalizing details of the big first stage. It was a mutually beneficial environment. With so many other irons in the fire, Marshall did not have the manpower to lavish on the S-IC, and Boeing got the chance to influence the outlines of the booster it would be building later. By the summer of 1962, Boeing had almost 500 engineers and technicians working on site at MSFC, and another 600 installed in a sprawling, hastily reconditioned cotton mill in downtown Huntsville known as the "HIC Building" (for Huntsville Industrial

STAGES TO SATURN

Center). Boeing's Huntsville operations concentrated on final hardware design and continuing liaison with MSFC.

Boeing also had about 450 people at Michoud, preparing for manufacturing operations. Michoud was also the management focal point for the S-IC, with the Saturn Booster Branch, under George H. Stoner, located there. From Michoud, Stoner presided over several far-flung elements. In Seattle, the company's home office, Boeing personnel carried out engineering and research support for Saturn, such as wind tunnel studies and other specialized engineering data. At Boeing's Wichita plant, the heavy tooling for Michoud was prepared, and subassemblies used in making up the tankage and other components of the booster were fabricated.

Michoud itself operated under Richard H. Nelson, with four sections for operations, quality and reliability assurance, engineering, and booster test. Engineering and manufacturing procedures were also laid out and coordinated with MSFC, covering a multitude of items, ranging from accidents, to test procedures, to the controlled use of precious metals, to "unplanned event reports." MSFC received many volumes of company reports, formal and informal, regarding the progress and problems of both the S-IC stage and the Michoud operations. Annual progress reports to the Marshall center summed up company activities. Topics included road construction; lighting in conference rooms; electrical troubles in the S-IC lifting derricks; and changes in stage design, test stands, and production. The company also reported on its special training programs for new employees in some of the esoteric arts of welding large space vehicles, radiographic inspection, and several varied courses in a number of specialized skills for production of booster rockets.⁴

This unusually intertwined work between government and contractor prompted Stoner at one point to ask von Braun, somewhat plaintively, why pick on Boeing? Why not allow the company to forge ahead on its own, like Douglas and North American? MSFC stemmed from the Redstone Arsenal, and MSFC managers intended to maintain an in-house capability. As von Braun once explained, contractors might present beautifully turned out pieces of sample hardware, expounding the virtues of exotic lightweight alloys and advanced welding technology. MSFC remained skeptical. Highly finished work on small samples was one thing. What about welding very large, oversized segments together where alignment and integrity of weld were very tricky to achieve? MSFC wanted to maintain its expertise, to make sure that alloys and welds would really work before the manufacturer began production. In this respect, Matt Urlaub, MSFC's manager for the S-I stage, suggested additional reasons for staying close to Boeing. All of Marshall's stage contracts went to companies accustomed to working under Air Force jurisdiction, a situation that gave the companies considerable latitude in

THE LOWER STAGES: S-IC AND S-II

technical design, fabrication and manufacturing procedures, and day-to-day operations. These companies were also principally airframe manufacturers. Marshall felt, however, that it had great competence in R&D, building prototypes, and technical management in rocketry. Therefore, Marshall should exert considerable influence in its areas of expertise early in the game, then let the contractors handle the production aspects. Douglas (with the S-IV/IVB contract) and North American (the S-II contract) were to manufacture their respective stages on the West Coast, but Boeing was to manufacture the S-IC stage at Michoud—in Marshall's backyard, so to speak. So Boeing got an unusually close overview, and MSFC also got experience in how to handle its other contractors with Air Force experience.

Stoner later admitted that the close alliance with MSFC at the start had been extremely fruitful, working out problems before they arose, avoiding approaches that might have resulted in dead ends, and capitalizing on MSFC's engineering style and experience—especially welding technology—to avoid production difficulties and cost overruns. From his vantage point at NASA Headquarters, Milton Rosen accurately gauged the impact of MSFC on Boeing. All the expertise behind the V-2, Redstone, Jupiter, and Saturn I went into the S-IC stage, he noted. Any mistakes would have had to be Marshall's—and there were not many. "With Boeing, all the power of Marshall's engineering and experience went into that (S-IC) rocket," Rosen said.⁵

TOOLS AND TANKAGE

Consistent with the MSFC insistence on in-house experience and capability, Marshall built three ground-test stages of the S-IC and the first two flight models. With the planned S-IC production facilities at Michoud still being modified, the MSFC production not only gave Boeing and Marshall people valuable early production experience, but also offered earlier delivery dates for test and flight stages. Using the tooling built at Boeing's Wichita facility and later installed at Marshall, Huntsville produced the S-IC-T, the S-IC-S, and the S-IC-F, and the first two flight models, the S-IC-1 and -2. The "T-Bird," as it was called, was built for static test firing; the "S," as a structural test model for load tests (it had no engines); and the "F," as a facilities test stage (also with no engines) to send to Cape Kennedy to aid in the checkout of the launch complex assembly buildings and launch equipment. Manufacture of these stages started in staggered sequence during 1963. In addition, MSFC planned to make the first complete fuel tank at Huntsville; this would be the first item turned out on S-IC tooling. Based on early tests of the fuel tank, engineers intended to verify the design loads anticipated for both it and the oxidizer tank. Then production could proceed on all components.

STAGES TO SATURN

As MSFC finished using the initial batch of tooling equipment, it was sent on to Michoud for Boeing's subsequent use there, so that portions of several stages were under construction at the same time. Approximately 7 to 9 months were required to fabricate and assemble the tanks, the longest lead-time items, and about 14 months for the complete assembly of an S-IC. For its first unit, Boeing built a ground test dynamics model, the S-IC-D, giving the company production team at Michoud some experience before starting on its first flyable booster. The S-IC-D was planned to carry one genuine engine and four simulated engines. After shipment to Huntsville, the plan was to join this first stage with the S-II and S-IVB for dynamic tests of the total vehicle "stack" in a test facility at MSFC. One other test unit was produced at Michoud—a full-sized dummy model of the S-IC stage, billed as the largest mockup in the world. Built of metal, wood, fiberglass, etc., the mockup was primarily used to help fix the sizes and shapes of parts, test the angles of tubes and lengths, and see where wire bundles would run.

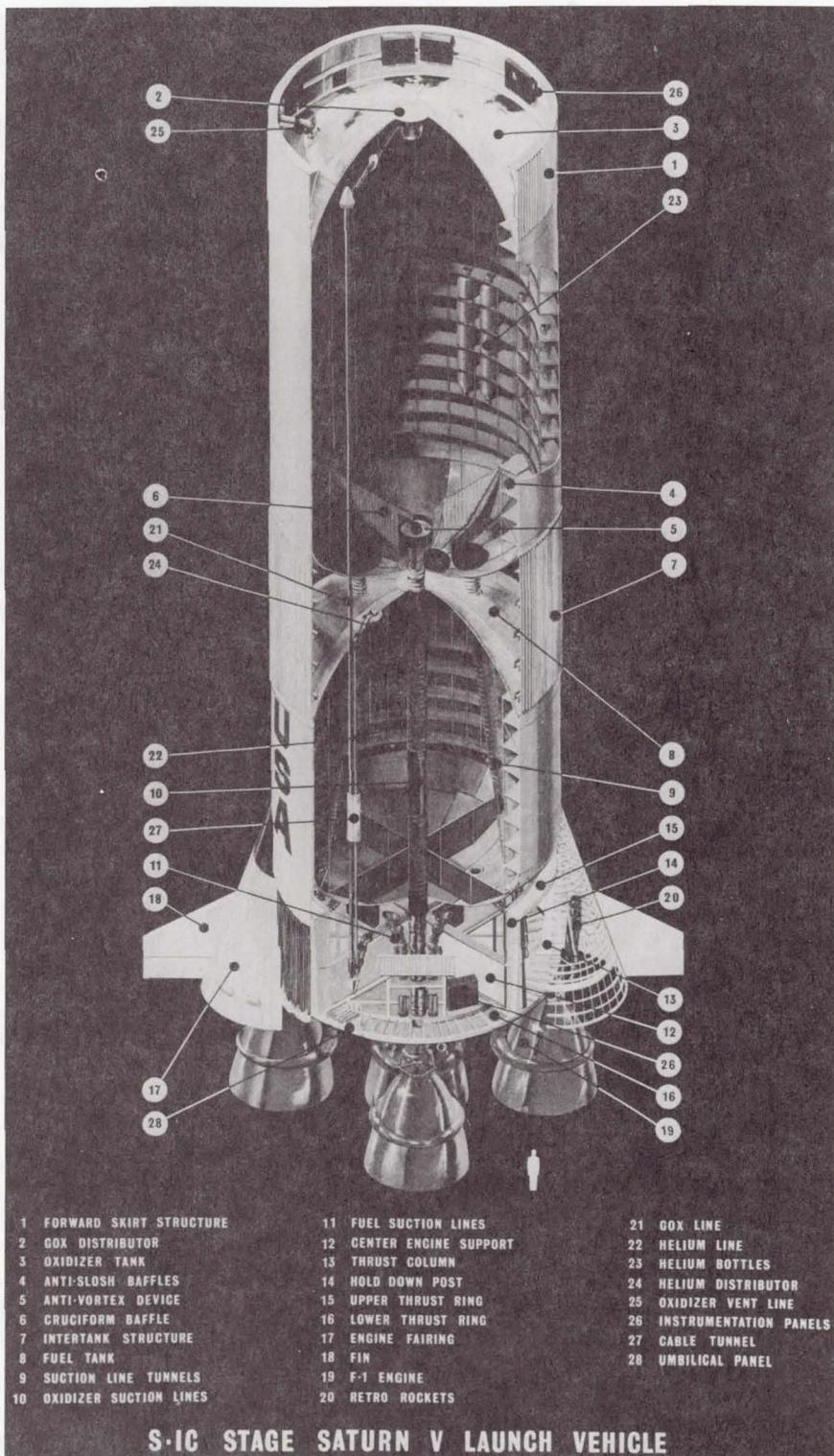
Because Chrysler produced the last Saturn I and Saturn IB first stages at Michoud, Boeing had to share the facility, but took 60 percent of the available space for the larger S-IC stage. The girth of the first stage also dictated removal of some of the overhead trusses and air conditioning ducts to allow a 12.2-meter clearance for fabrication of the stages. This left a slim 0.6-meter margin for the S-IC's 11.6-meter-diameter assembly fixture.

In addition, the heavy tooling required for the S-IC necessitated reinforcement of some parts of the floor. Boeing made another notable addition to the Michoud facility with the addition of a high bay area for assembly of S-IC components. In the early stages of talks on S-IC production, the question of horizontal as opposed to vertical assembly of the tanks and components came up. The vertical assembly mode was selected, even though a new high-bay area was required, because horizontal assembly posed problems in maintaining accuracy of joints in the heavy, but thin-walled tanks. In vertical assembly, gravity held the huge parts together, although a 198-metric-ton crane was required to hoist the parts atop each other, and to lower the completed booster back to the horizontal for final finishing.⁶

COMPONENTS: FEW BUT CUMBERSOME

Major components for the S-IC included the thrust structure, fuel tank, intertank, liquid oxygen tank, and forward skirt.⁷ As with nearly every other major segment of the towering Saturn V, these items were elephantine in their proportions.

The S-IC thrust structure absorbed the punishment of five F-1 engines at full throttle and redistributed the forces into uniform loading around the base of the rocket. The thrust structure also provided



S-IC STAGE SATURN V LAUNCH VEHICLE

STAGES TO SATURN

support for engines and engine accessories, and miscellaneous equipment. There were also four "anchors" helping to hold the vehicle in place prior to liftoff. These aluminum forgings, some of the largest ever produced in the United States, were made in one of two presses in the country capable of 50 000 metric tons of pressure to form the basic forged billets, 4.3 meters long and 816 kilograms in weight. A tape-controlled milling machine carved out the multiple cavities, flanges, and attachment holes, leaving a finished product weighing almost one-third less. One of the distinctive features of the Saturn launch vehicle was the presence of four engine fairings and fins at the base of the S-IC and mounted on the exterior of the thrust structure. The fins added considerable stability to the vehicle, and were fabricated from titanium to withstand the 1100°C heat from the engine exhaust. The four conical engine fairings smoothed the air flow at the base of the rocket and protected the engines from aerodynamic loads. In addition, each fairing carried a pair of retrorockets to decelerate the big booster after separation from the S-II stage; the retrorockets exerted a thrust of about 400 000 newtons (90 000 pounds) during a burn time of less than a second.⁸

The propellant tanks included special fill and drain points to handle heavy-duty lines used to fill the big vessels at high rates; up to 7300 liters (2000 gallons) of RP-1 per minute. If left to its own devices inside the tank, the RP-1 would have settled into strata of varying temperatures, a highly undesirable situation, so the S-IC incorporated a fuel conditioning system to "stir" over 730 000 liters (200 000 gallons) of RP-1 gently by continuously bubbling gaseous nitrogen through the feed lines and the fuel tank prior to launch. To ensure proper engine start and operation, a fuel pressurization system contributed to good pressure at the fuel turbopump inlets where 10 fuel lines (two per engine) funneled RP-1 to the engines at 4900 liters (1350 gallons) per second. During the countdown, pressurization was supplied by a ground source, but during flight, a helium pressurant was supplied from elongated bottles stored, not on the fuel tank, but submerged in the liquid oxygen (LOX) tank. In this medium, the liquid helium in the bottles was in a much more compatible environment, because the cold temperature of the liquid helium containers could have frozen the RP-1 fuel. There were additional advantages to their location in the colder LOX tank. Immersed in liquid oxygen, the cryogenic effect on the aluminum bottles allowed them to be charged to higher pressures. They were also lighter, because the cryogenic environment permitted manufacture of the helium bottles with one-half the wall thickness of a noncryogenic bottle. Produced by the Martin Company, the four helium bottles, 6 meters long and 56 centimeters in diameter, were aluminum extensions of unique length. Ducts carried the cooling helium down through heat exchangers on the F-1 engines, then carried heated, expanded gaseous helium back to the top of the fuel tank for ullage pressure.⁹

THE LOWER STAGES: S-IC AND S-II

With a capacity of 1 204 000 liters (331 000 gallons), the LOX tank acquired its payload in stages, with a slow fill of 5500 liters (1500 gallons) per minute and a faster fill at a torrential rate of 36 000 liters (10 000 gallons) per minute. The special problem of the LOX tank involved the feed lines leading to the thirsty engines about 15 meters below the fuel tanks. To do the job, the S-IC used five LOX suction lines, which carried oxidizer to the engines at 7300 liters (2000 gallons) per second. To achieve such high rates of flow, the lines could not be bent around the outside of the fuel tank; therefore, designers ran them right through the heart of the fuel tank. This in turn caused considerable fabrication problems, because it meant five extra holes in both the top and bottom of the fuel tank and presented the difficulty of avoiding frozen fuel around the super-cold LOX lines. The engineering fix on this included a system of tunnels, each one enclosing a LOX line, especially designed to carry an effective blanket of insulating air. Even so, the warmer fuel surrounding lines created some thermal difficulties in keeping the LOX lines properly cool. So the S-IC used some of its ground-supplied helium to bubble up through the LOX lines, and kept the liquid mixed at a sufficiently low temperature to avoid destructive boiling and geysering, or the creation of equally destructive cavities in the LOX pumps. To pressurize the tank, the S-IC tapped a helium ground source prior to launch. In flight, the LOX tank pressurization system used a system that tapped off some of the liquid oxygen, ran it through a heat exchanger to make it gaseous (called, naturally, GOX), and routed it back into the LOX tank.

Because the immense fuel and oxidizer vessels were separate items, the S-IC required additional pieces of hardware to make an integrated booster stage: the intertank and forward skirt. The intertank structure was a full seven meters in height itself, because the large bulges of the forward fuel tank dome and aft LOX dome extended inside it. There was a considerable amount of space remaining inside the intertank structure, which was given over to instrumentation cables, electrical conduit, telemetry lines, and other miscellany. Unlike the smooth skins of the propellant tanks, the unpressurized intertank structure required other means to maintain rigidity and carry the various stresses placed on it during launch. This requirement explains the distinctive appearance of both the intertank and the forward skirt, fabricated of 7075 aluminum alloy with corrugated skin and internal stringers (versus 2219 aluminum for the tanks). Both structures also included various access doors and umbilical openings for servicing, inspection, and maintenance prior to launch. The forward skirt, three meters in height, enclosed the bulge of the LOX tank's forward bulkhead, and its upper edge constituted the separation plane between the S-IC and the S-II stages.

While Rocketdyne supplied the five F-1 engines, the hydraulic system, used to actuate the gimbals, was included as part of the S-IC design. The hydraulic system featured a somewhat unconventional but

STAGES TO SATURN

convenient approach, using RP-1 fuel as the actuating fluid. Although not unique, this use was not common practice in rocket engines. RP-1 fuel admittedly displayed certain drawbacks as a hydraulic fluid: it was less viscous, more corrosive, a poor lubricant, presented contamination problems, and posed a safety hazard with its relatively low flash point. Still, the use of RP-1 was appealing because it eliminated a separate hydraulic system. The RP-1 was taken directly from the high-pressure fuel duct, routed to the gimbal system, then back to the engine fuel system. To compensate for the shortcomings of RP-1 as the fluid, special care was taken in the design of valves, and a less volatile fluid (from an external source) was used when testing indoors and during prelaunch activities.

The S-IC carried a heavy load of instrumentation, particularly in the first few flights, to record and report information on its components, temperatures, pressures, and so on, totaling about 900 separate measurements. Much of the success of this complex web of instrumentation rested on the stage's transmitters and Boeing's achievement of some significant advances in the state of the art. A company team redesigned and rebuilt a 20-watt transmitter with solid-state components, rather than vacuum tubes. Relying on integrated circuits, such units were reduced to half the size of a pea, doing the same job with higher reliability than older units the size of a baseball.

The first two flight stages of the S-IC also carried visual instrumentation that yielded some unique and striking images. A pair of TV cameras covered the fiery environment of engine start and operation. The cameras were tucked away above the heat shield—safe from the heat, acoustic shock, and vibration of the open engine area—and the lenses were connected to serpentine lengths of fiber optic bundles, focused on the engine area, and were protected by special quartz windows. Fiber optic bundles also provided a field of vision into the LOX tank, with a pair of motion picture cameras using colored film to record behavior of the liquid oxygen in flight. The system offered a means to check on wave and sloshing motions in the huge tank, as well as the waterfall effects of LOX cascading off internal tank structures during the boost phase. Another pair of color motion picture cameras captured the spectacular moment of separation from the S-II stage. Twenty-five seconds after separation, the color cameras were ejected in a watertight capsule, attached to a parachute for recovery downrange in the South Atlantic.¹⁰

FABRICATION AND MANUFACTURE

Although MSFC intended to have the S-IC developed and produced within the state of the art, the S-IC's mammoth dimensions created

THE LOWER STAGES: S-IC AND S-II

difficulties, not only in design, but in manufacturing and testing. In a speech to an annual meeting of the American Institute of Aeronautics and Astronautics in 1965, Whitney G. Smith, of Boeing's Launch Systems Branch, emphasized that "the tremendous size of this vehicle, coupled with its design complexities, have created many unique and challenging problems for the aerospace materials engineer." The basic complex challenge of the S-IC involved the scale of the stage itself in that it not only stretched the largest available tools to their maximum capacity, but also required the development of new techniques and facilities. Even old hands in the aerospace industry became fascinated by the size and scope of the S-IC stage fabrication and assembly, and magazines like *Aviation Week and Space Technology* featured blow-by-blow accounts of fabrication and welding procedures with technical asides on each step of the process.

The arm-in-arm approach of Boeing and MSFC in the early S-IC design studies continued into the development of jumbo-sized tooling and fabrication concepts for the stage. Under the watchful eye of Jack Trott, MSFC's deputy director of the Manufacturing Engineering Division at that time, tooling such as assembly jigs and weld fixtures were tested; once they were deemed workable, Boeing received approval to build duplicates for installation later at Michoud. This phase of tooling-up required a certain amount of flexibility in the tool manufacturing scheme, because each Apollo mission featured variations and required a slightly different S-IC for each launch. For this reason, the tooling had to have a high degree of changeability. Boeing also worked with smaller inventories (because of probable design changes), and planned built-in time allowance in the manufacturing scheme to accommodate changes to a vehicle already moving along the production line.¹¹

Some techniques did not work out, as in the case of chemical sculpturing of the outsized gore segments used for the curved bulkheads of the fuel and oxidizer tanks. Each bulkhead was made up to eight of the large gores, shaped like a wedge of pie, which had been made from a base segment and apex segment. The curved gores were manufactured with a precise tapering thickness toward the tip, and included a waffled pattern in the base segment. Because of the contoured shape and various raised surfaces, a chemical milling process seemed most attractive for sculpturing the curved pieces. But by 1965, trial-and-error development led Boeing to rely on machine milling of the gore segments in the flat, and then hydraulically bulge-formed to the correct contours.¹² The enormous bulge-formed dies to do this kind of job were located at Boeing-Wichita, where 90 percent of the parts for the S-IC were fabricated, then shipped to MSFC and Michoud to be manufactured into a complete booster stage.

In addition to bulge-forming gore segments from heavy aluminum sheets (up to 27.6 square meters in size), Boeing-Wichita devised a technique that simultaneously age-hardened and formed the large aluminum alloy plates in an electric furnace. The plates that made up the tank

STAGES TO SATURN

walls weighed five metric tons each, before they were milled down to weigh only one ton with walls about 60 millimeters thick. The tape-controlled form milling exposed the integral stiffeners, configured so that they were parallel to each other when the tank was in the curved condition. Mathias Siebel, director of MSFC's Manufacturing Engineering Laboratory, remarked that many test panels had to be machined to get the spacing and machine control tapes set up just right. Normally, the fabrication technique involved taking the 3.4×8 -meter plates and rolling them to shape, heat treating in a restraining fixture, then further processing to eliminate distortions. Using its electric furnace, the Wichita plant turned out integrally stiffened fuel and LOX tank walls by clamping the piece to a precisely curved fixture that was a built-in part of the furnace. In this way, tank walls were age-hardened by heat and formed in the same process.¹³

Eventually, the dozens of pieces of metal to make the S-IC tanks arrived at MSFC or Michoud to be welded together. The outsized dimensions of the pieces dictated modifications to standard welding procedures in which the welding tool was stationary and the piece to be welded was turned. Instead, the welding tools in most cases traveled along tracks over the components, held rigidly in huge jigs. The big problem was distortion, always a plague in the fabrication of light vessels (such as the Saturn tanks), and the S-IC propellant tanks were among the largest such lightweight vessels ever built. The primary cause of distortion was heat, and heat was unavoidable on the extended welding passes needed to make the vessel. Several actions were undertaken to reduce the heat and distortion factors. To ensure maximum weld conditions, the work was conducted in special areas with temperatures below 25°C and the humidity below 50 percent. Otherwise, too many weld defects occurred in the work. In addition, special techniques were employed at the welding surface, particularly the use of the tungsten-inert-gas (TIG) process. The TIG method had been used in other applications but never to such a great extent as in the fabrication of aluminum tanks for Saturn. The inert gas shield protected the weld from air, offered more control of the process, and allowed anywhere from 2 to 30 passes over a single weld joint. An S-IC had about 10 kilometers of welding with every centimeter inspected. Under these constraints, welding teams numbered between 10 and 15 specialists, with procedures lasting up to eight hours and sequenced like the countdown of a launch vehicle.¹⁴

Major welding operations entailed the joining of base and apex segments of the bulkhead gore segments into complete domes for the fuel and LOX tanks. The domes presented some difficult welding challenges when it came to welding various fittings and the several duct lines, because high residual stress in the huge curved components occasionally created a distortion effect known as "oil-canning." The distortions produced uneven surfaces that in turn upset the close

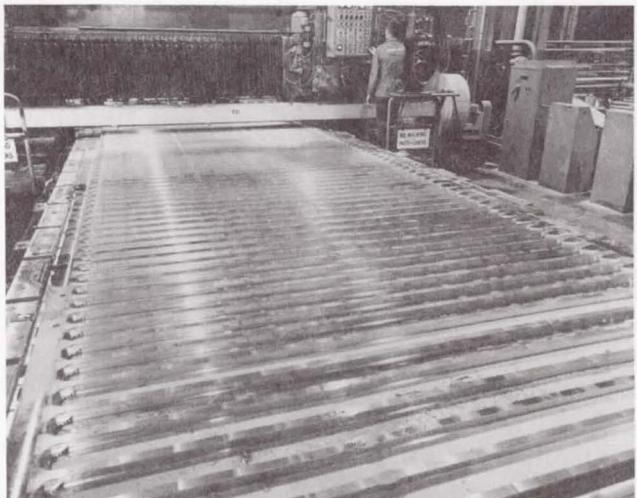
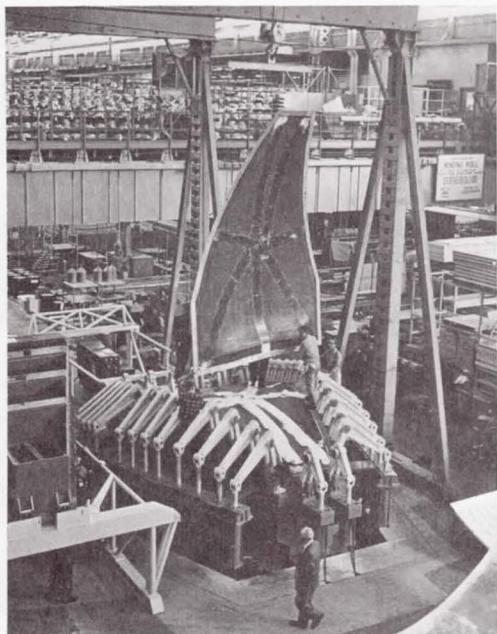
THE LOWER STAGES: S-IC AND S-II

tolerances required for other welding operations. The LOX duct lines, for example, were welded to fittings in the curved bulkhead. Specifications allowed no more than 0.5 millimeter mismatch between the duct and the bulkhead fitting, involving a bias-cut joint 63 centimeters in diameter. Rather than return to a time-consuming process of age-forming in a special fixture, MSFC developed a special "electromagnetic hammer" to iron out the distortions. High voltage passing through a large coil created opposing fields between the distorted part and the "hammer." The opposing fields repelled, and because the mass of the coil was greater than the mass of the part, the part actually moved to eliminate the distortion. There was no physical impact between the part and the coil. In fact, demonstrators liked to lay a sheet of tissue paper between the coil and part, proceed with the "hammering," and remove the tissue undamaged.

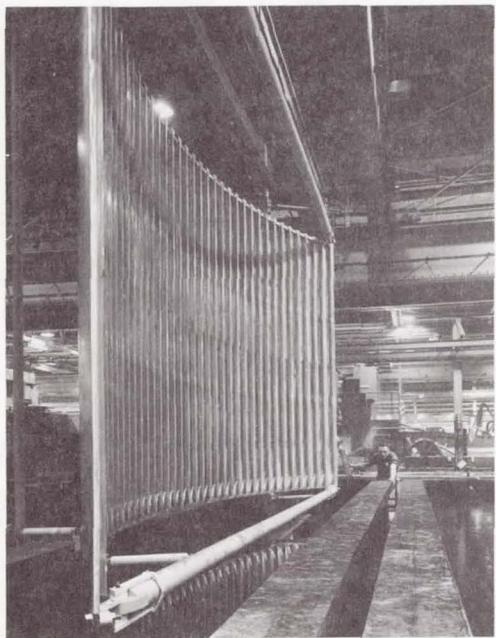
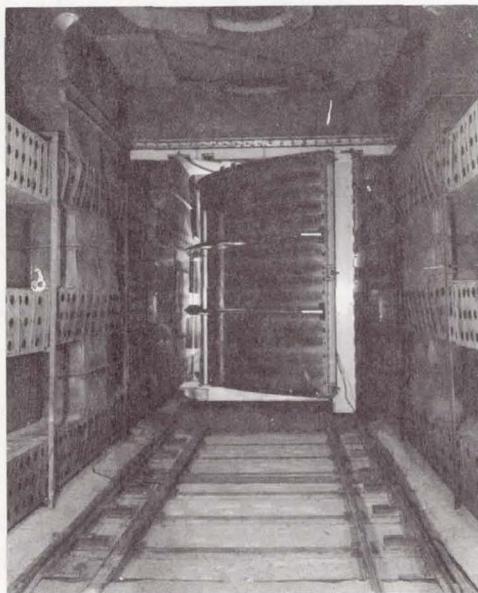
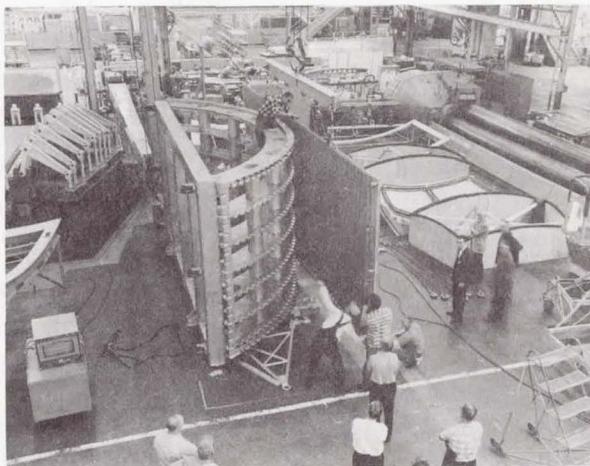
After several materials were rejected, the aluminum used in the fuel and LOX tanks was a 2219 alloy, chosen because of its variations in size, required for the S-IC, its weldability, and its resistance to stress corrosion. The propellant tank walls were welded into king-size hoops (10-meter-diameter), two for the fuel tank cylinder and four for the LOX tank cylinder. The tank cylinders included numerous circular slosh baffles designed for structural circularity and for slosh control. Additional slosh control was created by the installation of cruciform slosh control baffles in the aft domes of the fuel and LOX tanks.¹⁵

Before the components of the propellant tanks were welded, they were subjected to special cleaning processes, with most attention given to the LOX tank. For all its desirability as an oxidant, LOX is highly volatile under certain conditions presenting unusual problems in the handling and fabrication of parts in contact with the oxidizer. Mixed with a hydrocarbon like grease or oil, LOX becomes extremely unstable, and even a very small spark can ignite the capricious stuff. Theoretically, if a worker left a fingerprint on the inside of a LOX tank, the oil in the fingerprint could cause an explosive situation. So, all surfaces coming in contact with LOX were kept virtually spotless with a rating of "LOX clean". At Michoud, Boeing prepared a series of big vats for cleaning components such as valves, tubes, and tank wall segments.

Depending on the specifications, several different cleansing processes could be used and technicians wore special lint-free gloves. A typical operation began by spraying the part with a degreasing compound, followed by washing in a detergent solution. Rinsing required water that had been carefully de-ionized and decontaminated. The part was then de-oxydized with a solution of nitric acid and rinsed once more—but only in preparation for additional cleaning. After being heated, the part underwent the next step; an etching process that actually removed a micro-thin layer of surface material. Following a final rinse, drying was done with a blast of hot air, which was especially filtered to be oil-free. In addition to the cleaning of the segments, subassemblies like bulkheads



Top left, Boeing's Wichita plant is bulge forming the bulkhead of the S-IC first stage of the Saturn V. Above, 23 numerically controlled programming tapes control machining of the 3.4×7.9 -meter aluminum alloy plates that become skin panels for the S-IC stage. Opposite, top, the skin panel is being positioned for attachment to the curved restraining fixture. Opposite, center, now curved to precise contour on the fixture, the panel is rolled into an electric furnace for age-hardening. Bottom, the finished panel emerges, ready for dipping treatment to remove impurities.



STAGES TO SATURN

also received the cleaning treatment in Boeing's "major component cleaning facility," jocularly known at Michoud as "the world's largest dishwasher." The dishwasher, a box 12 meters square and 6.7 meters high, was lined with stainless steel. A complete tank bulkhead was rolled in and washed down with special chemicals dispensed from revolving pipes outside and inside the dome. The revolving pipes and spraying action made the nickname inevitable.¹⁶

When it came to joining the tank wall cylinders and domes together, the size of the S-IC required the production of a special rig known as the Y-ring. The longest "lead-time" item in the S-IC manufacturing process, the Y-ring required two months to complete at Michoud. It consisted of three aluminum billets welded into a ring and then carefully machined to the correct shape in several closely controlled phases.¹⁷ The Y-ring was designed to eliminate lap joints where the tank domes, walls, and adjoining structure (like the intertank segment) came together. Each Y-ring featured one straight side as the meeting point for the vertical sides of the tank well and adjoining structure, and one appropriately angled area to serve as the meeting point for the upper or lower tank dome.

In the vertical assembly area at Michoud, complete fuel and LOX tanks were formed and then hydrostatically tested to 105 percent of the total pressure anticipated in a mission. This overpressurization created a certain amount of danger in the test area, so the test was monitored by a bank of closed circuit TV cameras. Demineralized water was used in the test sequence, with special dyes added to show up on the cameras if minute seepages occurred. The hydrostatic tests exerted so much force on the tanks that their dimensions were actually stretched by 1.3 centimeters at the bottom. After flushing and cleaning procedures, the tanks were accurately calibrated for the exact propellant capacity by refilling with water of an established weight, temperature, and specific gravity. The entire S-IC was then stacked from the bottom up, beginnng with the thrust structure, and attached together at the Y-ring juncture with special fittings. The completed S-IC was loaded on a special dolly and moved to the low-bay area for the installation of engines and miscellaneous equipment. It was moved very carefully, however, because the horizontal stage on its transporter had only a 14-centimeter roof clearance.

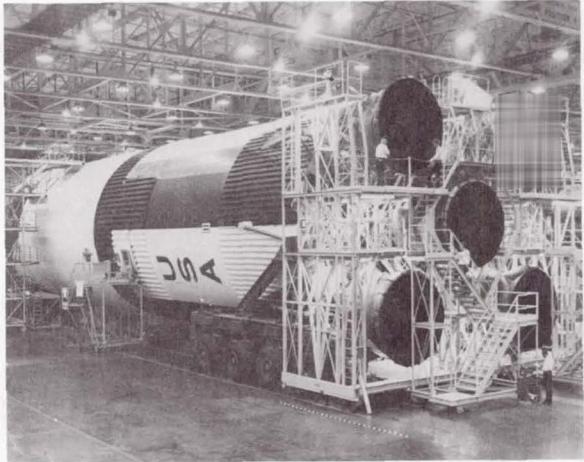
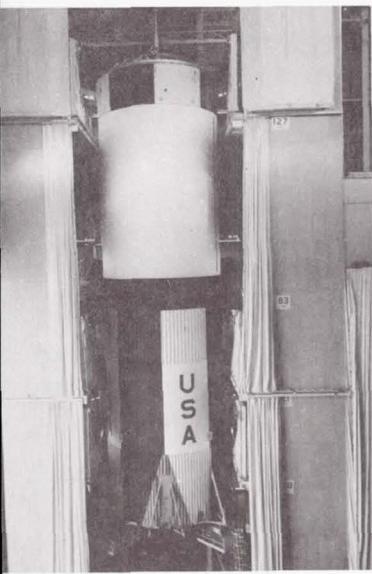
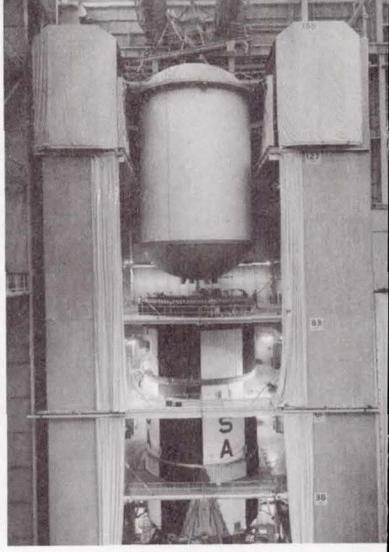
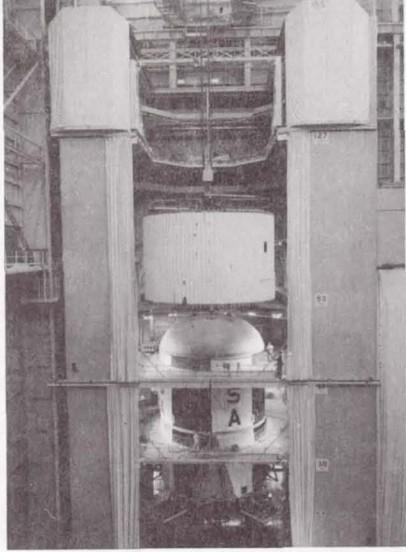
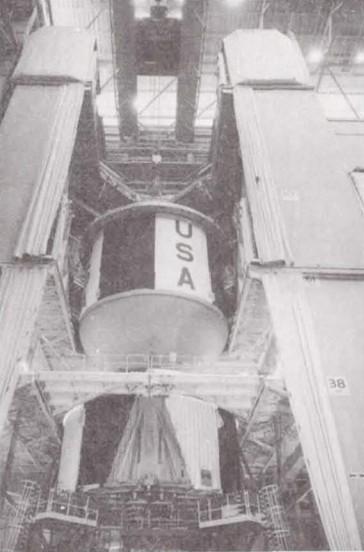
The hydrostatic tests were only a part of thousands of tests, large and small, conducted on the S-IC before launch. At both Michoud and MSFC, all kinds of x-ray tests, load tests, and other examinations were made to ensure the stage's fitness. Before static test firing, for example, S-IC stages spent 10 full weeks in a test cell at Michoud for scrutiny of the completed stage all around and hundreds of separate test sequences.¹⁸ The most spectacular tests—and test facilities—for the S-IC involved the static firing of the five F-1 engines at full thrust. Two S-IC static test

THE LOWER STAGES: S-IC AND S-II

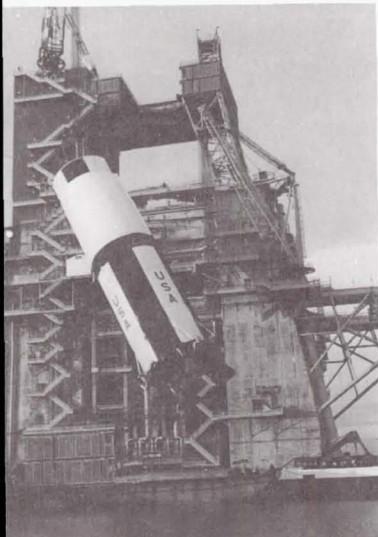
stands were available, one at Huntsville and the other at the Mississippi Test Facility; both were similar in size and construction. The MTF facility was designed to include two test positions. Although MSFC conducted the first static tests of the S-IC in the summer of 1965, the MTF stand for the S-IC began operations about a year later and became the focus of the static test firing program. It seemed quite appropriate that the howling, thunderous roar of the S-IC cluster could so often be heard at an area originally known as Devil's Swamp.

At the time it was declared operational in 1966, the 124-meter-high test stand at MTF was the tallest building in the state of Mississippi. The concrete and steel tower rested on 1600 steel pilings, each 30 meters long, and the S-IC was secured by four huge hold-down arms anchored to a slab of concrete 12 meters thick. The massive jaws of the restraining arms clamped onto the rocket tail by means of drive mechanisms geared to move only 8 centimeters per minute. From a distance, the big test tower looked like a concrete monolith; its hollow legs were the equivalent of a 20-story building with offices, machine shops, data centers, and elevators. With the huge volume of LOX and kerosene in the rocket tanks, a catastrophic fire during testing was always a consideration; as a result all personnel were evacuated to remote bunkers before ignition. In case of a fire during a test, a water deluge system, evidenced by the myriad of pipes lacing up and down the structure, could spray 782 000 liters (215 000 gallons) per minute over the stand. Moreover, engine tests required a second water deluge system that supplied the stand with 1 100 000 liters (300 000 gallons) of water per minute through a double-walled steel flame bucket directly below the F-1 cluster. Thousands of holes in the outer walls of the flame bucket allowed water to gush out to cool the bucket and keep it intact for the next test. During a five-minute test run, the S-IC test stand got enough water to supply a city of 10 000 for a day.¹⁹

Any problems in the S-IC program seem to have occurred mostly at the start but were resolved before a serious impasse developed. Matt Urlaub recalled early confrontations between various Boeing and Marshall people over management issues. "Boeing . . . had a very strong sense of accomplishment up to that point, and they knew they had built large airplanes before, and this [S-IC] vehicle isn't much different . . . and we were, in those days, a pretty proud organization too." Both sides eventually adjusted, however, "getting the pecking order straight," as Urlaub put it. In 1963 the S-IC program encountered a succession of welding problems that persisted throughout the next year. Portions of the S-IC-T vehicle were scrapped because of welding deficiencies in the propellant tanks, and the S-IC-T generally lagged six weeks behind schedule during 1964. An upper LOX tank bulkhead for S-IC-S was scrapped "due to poor quality" in October, and at the same time, the manufacturing schedule for S-IC-T was reported to be 19 weeks behind



At Michoud, the big S-IC stage of the Saturn V is assembled, or "stacked," in the high bay. Top left, the fuel tank is lowered into the lower skirt; at top center, the intertank assembly is fitted to the fuel tank; at top right, the oxidizer tank is added; above, left, the forward skirt assembly is attached. Then the five F-1 engines are attached (above, right) and the completed stage is shipped to the Mississippi Test Facility and hoisted into the test stand (left) for static-firing tests before shipment to the Kennedy Space Center where the total flight vehicle will be stacked, checked out, and launched.



THE LOWER STAGES: S-IC AND S-II

schedule because of a shortage in parts for the thrust structure. By November, Urlaub cautioned that the S-IC program was still behind schedule in several areas. The S-IC-1 flight stage, for instance, was lagging by three months. "Although the S-IC program may appear to be in the shadow of the S-II program," Urlaub said, "I think it would be unwise to pretend that now the entire Saturn program is paced by the upper stages."²⁰

When the S-IC finally began its static firing tests in 1965, the chances for success of the Apollo-Saturn program brightened considerably. Early in 1966, the S-IVB stage was operational aboard the Saturn IB vehicle. The gloomiest clouds on the horizon in 1965–1966 were hovering over the North American plant on the West Coast, where the S-II second stage was still under development.

THE S-II: CONCEPTS

The vague outlines of the S-II took shape within the report of the Silverstein committee in December 1959, when its members recommended the development of the high-thrust, liquid-hydrogen-fueled engine. In less than a year, Rocketdyne won the contract for the J-2 engine. Because many of the engine design parameters depended on stage configuration and mission profiles, designers had also begun parallel design studies on the stage itself. These studies sprang from the Silverstein committee's original report, which included a LOX-LH₂ propellant S-II stage (see chapter 2). Within weeks of the Silverstein committee's report, design and engine studies were in progress, and correlated, so that many features of the S-II design were under consideration more than 12 months before NASA began action for stage procurement.²¹

On the eve of his departure as Administrator, T. Keith Glennan wanted to make sure that an S-II stage received his successor's strongest attention. The only question was when to move. Glennan hedged a bit in January 1961, when Major General Don R. Ostrander, Director of the Office of Launch Vehicle Programs, pushed for definition of the C-2 vehicle configuration, including initiation of contract work for the S-II. Glennan hesitated because he did not want to "bind the new Administrator to an expenditure which will run several hundred millions of dollars," and because he felt it wiser to see how the J-2 engine program progressed. There was no doubt in his mind, however, concerning the desirability of the S-II stage as part of the C-2. The C-1 vehicle did not have the capabilities NASA needed for the long term. "The Saturn program is left in mid-stream," Glennan emphasized in the transition memo he left for his successor, "if the S-II stage is not developed and phased in as the second stage of the C-2 launch vehicle."²²

Glennan's memo reflected the strong trend within NASA to move

STAGES TO SATURN

toward a bigger vehicle with an LH₂ stage, and not long after Webb's confirmation as the new Administrator in 1961, NASA authorized the Marshall center to proceed with contractor selection. MSFC's invitations to a preproposal conference in Huntsville in April attracted 30 aerospace firms. As described by MSFC at that time, the S-II second stage of the Saturn C-2 vehicle was presented as the largest rocket project, in terms of physical size, to be undertaken by American industry. Powered by four of the new J-2 engines, the preliminary configuration of the second stage was given dimensions of 22.5 meters in length and 6.5 meters in diameter. The implied challenge must have been sobering, since 23 of the companies did not submit proposals the following month for the first phase of the S-II contractor selection process. The seven firms left in the running included Aerojet General Corporation; Chrysler Corporation, Missile Division; Convair Astronautics Division of General Dynamics Corporation; Douglas Aircraft Corporation; Lockheed Aircraft Corporation, Georgia Division; Martin Company; and North American Aviation, Incorporated. They submitted briefs to MSFC concerning their experience and capability as potential contractors for the S-II stage.²³

By June the contractors had been rated by a source evaluation board using a numerical scoring system geared to the phase one proposals. Three firms were eliminated, leaving Aerojet, Convair, Douglas, and North American. These four companies were about to receive a surprise, because NASA had decided to change the configuration of the second stage. On 8 June, Webb circulated a memo to his top advisors specifying that the Saturn C-2 simply could not boost the Apollo spacecraft to the escape velocity required for a circumlunar mission. NASA was now considering the C-3, which consisted of a fatter first stage powered by two F-1 engines and a larger S-II stage. As Webb noted, the C-3 had not yet been approved,²⁴ and the four contractors, gathering late in June for the phase two conference, discovered they would have to grapple with some very loose ends.

The phase two conference opened with remarks by Oswald Lange, Chief of the Saturn Systems Office. In his initial statement, Lange explained why the C-2 configuration was going to be bypassed in favor of the C-3. Recent research on the problem of radiation in space indicated that the spacecraft needed more shielding, which would increase spacecraft weight from the original 6800-kilogram estimate to 13 600 kilograms. Moreover, Lange revealed, the original S-II diameter of 6.6 meters was now enlarged to 8.13 meters to be more compatible with the C-3's first stage and allow better payload flexibility in the future. On the other hand, Lange said, he was not able as yet to give the contractors hard figures on the exact configuration of the stages above the 8.13-meter S-II (making it difficult to figure out the mechanics of boost, separation of upper stages, and other aspects, as one contractor noted); indeed, MSFC might decide on an even larger 9.14-meter stage! "It may be a little hard

THE LOWER STAGES: S-IC AND S-II

for you to speculate a design if we give you such soft indications of the configuration that we ultimately want," Lange admitted, but pledged to have firm numbers when Marshall and the winning contractor sat down to hammer out the details in final contract negotiations.

In a question-and-answer session that followed, a Marshall spokesman, after elaborating on some of the aspects of the proposals, apologetically echoed Lange, and explained that Marshall was anxious to get started on the contracts. "You can see that we have a whole lot of doubt in what we say here, and there are a lot of conflicting problems," the spokesman admitted. "We are presently trying to resolve them. We could have asked you not to come here today and could have taken, say, six weeks time to resolve these problems internally, in which case we would have lost six weeks on the S-II contract." Speaking with candor, he told the contractors, "This of course puts the monkey on your back, and we know that!" However, even with all of this looseness in the preliminary stages of finalizing the contract, Marshall made it clear that firm figures for the stage would be forthcoming, and that contractors would be held strictly accountable. As Wilbur Davis, of the MSFC Procurement and Contracts Office, stated it, "I wish to emphasize at this point that the important product that NASA will buy in this procurement is the efficient management of a stage system."²⁵ Ironically, it was this very point that later contributed so much stress in relations between NASA and its chosen contractor.

North American won the prize; NASA announced the company's selection for the S-II contract on 11 September 1961.²⁶ After consultation and search for a manufacturing site, a location at Seal Beach, California (not far from Long Beach), was chosen, and the facilities for constructing the S-II were built by the government. Coordination between North American, NASA, and the Navy, designated as the government's construction agency, did not always proceed well, and led to the dispatch of NASA investigation teams from Headquarters. In spite of the problems in the three-way arrangement, D. Brainerd Holmes emphasized in the spring of 1963 that "we are getting these facilities on time and the construction is excellent." By early autumn, North American was putting together the first S-II hardware components.²⁷

S-II CONFIGURATION

The S-II turned out to be a comparatively advanced stage in terms of the existing state of the art. Although the S-II carried about 426 400 kilograms of liquid oxygen and liquid hydrogen, the tank structure, though supporting the structural mass, accounted for just a shade over three percent of the stage's total fueled weight. A common bulkhead much larger than that in any previous rocket averted the need for an

STAGES TO SATURN

interstage between the oxidizer and fuel tanks; this reduced the total length of the stage by over 3 meters and saved about 4 metric tons of extra weight. In technical terms, the fabrication of the bulkheads called for unusually demanding accuracy in meridian welds that joined the bulkhead gores together. The welding operation joining the curved, 6-meter-long seams together had to be made to specifications allowing less than 0.33 millimeter of a mismatch. Then there was the problem of insulating the big liquid hydrogen tank, filled with thousands of liters of the super-cold propellant. Otherwise, the basic design elements of the S-II seemed conventional enough in that it consisted of eight major structural components and six major systems, all of which reflected the usual kind of basic elements associated with both the S-IC and the S-IVB.²⁸

The vehicle was assembled at Seal Beach, where most of the major structural elements were fabricated. Exceptions were the interstage, aft skirt, thrust structure, and forward skirt which were produced at North American's plant in Tulsa, Oklahoma. The interstage, aft skirt, and forward skirt, all of semimonocoque construction, had been designed for structural rigidity. The thrust structure (in the usual inverted cone shape) featured both high-strength riveting and thrust longerons to handle the full thrust of the J-2 engine cluster. Fabricated in separate pieces, the aft skirt and thrust structure were intended to serve as a single structural entity when joined together. The combination served as a mounting point for the five engines, the heat shield, and assorted plumbing and black boxes.

In a sequence known as dual-plane separation, the interstage, although joined to the aft skirt, uncoupled from the S-II after staging from the S-IC. Following burnout of the first stage, a linear-shaped charge separated the S-II from the S-IC; this procedure was simultaneous with the firing of S-IC retrorockets and eight ullage motors on the interstage of the S-II. About 30 seconds after first-stage separation, the S-II interstage separated from the second stage itself. Initiation of the dual-plane separation maneuver occurred when the outboard J-2 engines reached 90 percent of their maximum thrust; at this point, explosive charges were triggered, which severed the interstage. The maneuver required a precise separation that would propel the interstage (5.4 meters long) rearward, clearing the engines by approximately 1 meter, while the S-II was accelerating to its blinding top speed. Once free of the interstage mass, the performance of the S-II was greatly enhanced. The dual-plane separation was an alternative to a method called "fire in the hole," which involved ignition and separation of the S-II while still in contact with the interstage but not attached to it. Designers preferred to avoid this alternative because of possible perturbations and oscillations at the end of the first-stage boost phase. With the S-II accelerating on an even course, it was easier to drop the interstage during that phase, rather

THE LOWER STAGES: S-IC AND S-II

than risk hitting a wobbling interstage attached to the S-IC as the S-II pulled out.

The LOX tank of the S-II stage, like that of the S-IVB, incorporated the principle of the common bulkhead, which comprised the top half of the LOX tank. With its 10-meter diameter and 6.7-meter height, the ellipsoidal container had a squat appearance. Having no vertical walls to speak of, the LOX tank was constructed by welding together a dozen gores and finishing off the tank with "dollar sections," large circular pieces joining the ends of the gores at the top and bottom. The top of the LOX tank actually formed one half of the common bulkhead. After welding this part of the LOX tank, the common bulkhead was completed before adding the tank's bottom half to it. Early on, the forming of the gore segments for all the bulkhead assemblies frustrated manufacturing engineers, because no techniques existed for forming such large, unwieldy pieces. Each gore was approximately 2.6-meters wide at the base and had complex curvatures that were difficult to form accurately. After rejecting numerous possible procedures, the manufacturing team finally chose a somewhat exotic method—underwater explosive forming. This technique quite literally blasted the wedge-shaped gores into shape. North American's Los Angeles Division produced the gores, using a 211 000-liter (58 000-gallon) tank of water at nearby El Toro Marine Base for explosive, or "high-energy," forming. After positioning the gore segment in the tank, engineers detonated a carefully located network of primacord explosive, forming the metal by the blast transmitted through the water. The formation of each gore required three separate blasts.²⁹

At the start of the S-II program, MSFC questioned North American's proposals for a common bulkhead. Despite the S-IV stage common bulkhead, engineers at Huntsville remained skeptical of North American's ability to produce a common bulkhead of the S-II diameter that would also withstand the additional stresses and pressures of much greater volumes of cryogenic propellants. Marshall insisted on parallel backup schemes using more conventional bulkhead designs, in case North American's idea failed. On the other hand, North American insisted on its common bulkhead to reduce stage length and weight from the conventional form of two separate fuel and oxidizer tanks connected by an interstage component. The company had to work out several new fabrication techniques to do the job.³⁰

Beginning with the upper half of the LOX tank, fabrication of the common bulkhead required a number of carefully timed and sequenced operations. First, honeycomb phenolic insulation was fitted over the upper surface of the LOX tank dome, called the aft facing sheet because it served as the bottom of the common bulkhead. Then the insulation was bonded to the aft facing sheet and cured in a gargantuan autoclave. Next came the preliminary fitting of the forward facing sheet; this piece became the bottom half of the LH₂ tank (also formed from large

STAGES TO SATURN

wedge-shaped gores). Preliminary fitting of the forward facing sheet revealed surfaces in the insulation that needed to be filled in or shaved down for a perfect fit, using a machine controlled by data-tapes. Throughout the process, numerous checks were made to ensure that no gaps were left between the insulation and the facing sheets; ultrasonic equipment verified complete bonding of the adhesives.

Fitting the honeycomb core to the bulkhead domes was one of the most critical operations in the S-II manufacturing sequence. The chemically milled gores tapered from about 13 millimeters thickness at the base to 0.79 millimeter at the apex. With these thin sections, the great domes possessed relatively little strength by themselves and tended to sag; this situation created severe production problems in achieving the close fit required between the top and bottom domes and the insulation core. The honeycomb sandwich, which comprised the core, measured nearly 13 centimeters thick at the peak of the common bulkhead and tapered off at the bottom periphery, where more thickness was not necessary. So the honeycomb core, like the gores, had to be shaped to complex curvatures, tapered, and affixed without gaps to the flexible dome surfaces.

The procedure finally worked out by North American manufacturing teams was heralded by the company as "a major advance in missile fabrication." Workers applied a low pressure inflation force to the aft facing sheet, giving it full contour and providing accurate dimensional traces for fitting the honeycomb insulation core. The forward facing sheet presented a different problem; since the top surface of the insulation core had to be fitted to the underside of the forward facing sheet, the inflation technique was ruled out. Instead, NAA devised a huge vacuum bell. Fitted over the forward facing sheet, the vacuum bell sucked up the sheet to a fully contoured position. Afterward, handling slings lowered the entire assembly over the rigidly pressurized aft facing sheet to record the final set of dimensional traces for shaping the insulation surfaces.³¹

At the bottom edge of the forward facing sheet, a "J" shaped periphery provided the surface for welding it to the bottom cylinder wall of the LH₂ tank. These "J-section" segments had to be separately machined and form-fitted. A circular weld at the "J-section," joining the LOX and LH₂ tanks, was buttressed by a bolting ring; 636 high-strength bolts secured the bolting ring to flanges on the bottom LH₂ tank cylinder and to the aft skirt section. The bottom cylinder measured only 69 centimeters high; the remaining five cylinder walls, each 2.4 meters high, were fabricated in four sections and welded together. The curved aluminum skins were machine-milled to leave stringers and ring frames for both structural rigidity and for mounting the internal slosh baffles. The LH₂ forward bulkhead was fabricated of 12 gores, in much the same way as the LOX tank lower bulkhead.

Insulation for the LH₂ tank created some of the most persistent

THE LOWER STAGES: S-IC AND S-II

technical problems in the entire S-II program. North American chose external insulation, primarily for added material strength from the cryogenic effects of LH₂ inside the fuel tank. This trade-off confronted the company with the problem of adequate external insulation and with special difficulties in bonding the insulation to the super-cold surfaces of the fuel tank. The original solution specified external insulation made of phenolic honeycomb filled with a heat-resistant foam of isocyanate. Fabricated in panels, the insulation material was sealed at the top and bottom with a phenolic laminate followed by a layer of Tedlar plastic film. The process of bonding the insulation panels to the tank created potential hazards. Air pockets next to the super-cold metal could be turned into puddles of liquid oxygen; these puddles could eventually weaken the bonding, thereby allowing large panels to peel off. To avoid this, the S-II stage featured a liquid-helium purge of the insulation through grooves cut into the insulation surface next to the tank walls. Helium flowed through the grooves from the start of hydrogen loading through countdown and up to the instant of launch.

Unfortunately, this design never worked very well. The purge system was tricky, the insulation bonding repeatedly failed, and chunks of insulation continued to fall off during tanking and test sequences. Although several S-II stages were produced with the original insulation concept, the results were so discouraging that North American spent considerable time and money working up an alternative. Instead of making up panels and affixing them to the tank, the company finally evolved a process for spraying insulation material directly onto the tank walls (eliminating the air pockets), letting it cure, then cutting it to the proper contour. This technique turned out to be much more economical and much lighter than the insulation panels.³²

Eventually, all the parts of the S-II came together in the vertical assembly building at Seal Beach. Vertical assembly was chosen for its advantages in joining major parts and ease of welding. In vertical assembly, as opposed to horizontal assembly, it was easier to maintain circumference of the large diameter parts to close tolerances and gravitational force helped maintain stage alignment. Moreover, if the various cylinders and bulkheads were horizontal, temperature diversion about the circumference of the parts would produce distortions at the top of the piece being welded. Throughout each welding sequence, technicians employed a variety of special scopes, levels, and traditional plumb bobs to make sure alignments were exact. Additionally, the stage was subjected to hydrostatic, x-ray, dye penetrant, and other checks to ensure proper specifications. One of the last items to be added was the systems tunnel, affixed to the exterior of the stage. The tunnel, a semicircular structure, ran vertically up the side of the S-II and carried miscellaneous instrumentation along with wires and tubes that connected system components at the top and bottom of the stage.

STAGES TO SATURN

Final work inside the tanks included installation of slosh baffles, probes, and other miscellaneous equipment. In preparation for these operations, all surfaces inside the tanks were thoroughly cleansed, flushed with trichloroethylene, and dried. Flushing equipment consisted of a spray nozzle fitted to a movable lifting cylinder, similar to the hydraulic lifts used in filling stations. After the flushing, a team of technicians mounted a ladder and platform attachment on the movable lifting cylinder, entered the tanks, and began final installation of equipment. With all accessories installed, the tanks had to be flushed once again and the access ports sealed.

Finally, the engines were mounted, again using accurate aligning equipment to position each J-2 in the thrust frame attach points. Additional stage tests and systems checks preceded final preparation for shipping to the Mississippi Test Facility for the static-firing checks. After that—delivery to Cape Kennedy for launch.³³

S-II SYSTEMS

Of the six major systems, the propellant system was the most complex. The seven propellant subsystems included plumbing, hardware, and control to accomplish the following: purge, fill and replenish, venting, pressurization, propellant feed, recirculation, and propellant management. Elements were largely designed to cope with the tricky characteristics of the cryogenics carried on board the S-II stage. By using helium gas, the purge subsystem cleared the tank of contaminants like moisture (which could freeze and block valves or vents) in the LOX tank, and oxygen (which could freeze and create danger of explosions) in the LH₂ tank. The fill and replenish subsystem (along with the recirculation cycle), helped relieve the tanks, valves, pumps, and feed lines of the thermal shocks encountered from the sudden introduction of ultra-cold propellants into the stage.

The recirculation subsystem kept propellants moving through the engine pumps and associated plumbing while keeping them properly chilled and ready for operation. Similarly, the fill and replenish system brought the propellant tanks and their related plumbing down to a temperature suitable for loading of the cryogenic propellants. The procedure began by circulating cold gas through the tanks and lines, followed by a "childdown" cycle—slow pumping of propellants into the tanks until they reached the five percent level. Even with the preliminary cooling by chilled gas, the tanks were so much warmer than the propellants that much of the liquid boiled off when it first gushed into the tank; the "childdown" dropped the tank temperatures to a point where fast fill could then proceed. Because the propellants were pumped into the tanks hours before liftoff and a certain amount of boil-off

THE LOWER STAGES: S-IC AND S-II

persisted, constant replenishment was required until a minute or two before liftoff. Venting subsystems prevented overpressurization of the tanks, while a pressurization subsystem maintained propellant flow. Other subsystems for feeding the propellant from tanks to engines as well as propellant management (simultaneous depletion of tanks, engine cutoff, etc.) completed the propellant system network.

Other major systems (electrical, ordnance, measurement, thermal control, and flight control) were similar in basic functions to those on other Saturn stages. The same was true for the ground support operations for checkout, leak detection, engine compartment conditioning, and other equipment.³⁴

TRIAL AND ERROR: THE WELDING PROBLEM

The size of the S-II included dimensions normally associated with the bulky fittings and burly strength of heavy industry. The inside of the S-II was roomy enough to stack three standard railroad tank cars end to end, with room to spare for a caboose lying sideways on top. Yet, the 24.8-meter stage weighed only 43 100 kilograms in its dry stage (by comparison, the three empty tank cars would weigh more than 95 700 kilograms). In spite of its massive appearance, the S-II was honed to the precise standards of the watchmaker. Almost one kilometer of welded joints had to be surgically clean and flawless, and many had to be accurate to 0.33 of a millimeter. The structural efficiency of the stage, in terms of the weight and pressures taken by its extra-thin walls, was comparable only to the capacity of one of nature's most refined examples of structural efficiency, the egg.

Even with all this description of the meticulous workmanship lavished on the S-II, the layman still might enquire, "so what?" What was so challenging, to the platoons of engineers and technicians who did it, about welding together a big rocket stage? One problem was the nature of the tank skins themselves. The S-II was built of an aluminum alloy known as 2014 T6, which was not generally favored for welding. North American knew the welding job was going to be complicated but wanted to use the alloy because of its enhanced strength under cryogenic conditions. A theme of the entire Saturn program was "size," and the challenges inherent in the S-II were similarly challenges of magnitude. With a diameter of 10 meters, the stage required circumferential welds of 31.4 meters. The longer the weld, the tougher the problem of sustaining quality and close tolerances—and in the S-II, weld quality and close tolerances were essential. A high quality weld pass of 1 meter might be one thing, but a virtually flawless circumferential weld of 31.4 meters promised all manner of increasing heat input problems and attendant

STAGES TO SATURN

distortion problems where none could be tolerated. "I had very little gray hair when we started," admitted Norm Wilson, manager of the Manufacturing Engineering Section for the S-II at Seal Beach. "But look at me now," he said in 1968.³⁵

Wilson's gray hair owed much to the multitude of variations and requirements implicit in the plethora of tricky welding tasks all over the stage, aside from the circumferential jobs. The various aluminum sheets joined together in the welding process varied in shape, size, and thickness, all of which caused different problems for the welder. One such joint had skins that tapered from 16 millimeters thick down to under 6 millimeters, then back up to 13 millimeters. The shifting thicknesses frequently made temperamental men of normally even-tempered welding engineers; weld speeds, arc voltages, and other regimes had to be tailored for each variance during the welding pass. Minuscule cracks, tiny bits of foreign material in the weld seams, moisture, or other apparently innocuous imperfections could leak volatile propellants or cause catastrophic weaknesses under the pressures and loads experienced in flight.

"You can't really say our work has been exotic," Wilson said. "But when you consider the sizes, angles, lengths, designs, offset tolerances, and overall specifications involved, you have one challenging welding problem on your hands. We've had to tap our experience well dry and tax our imagination to come up with the right answers, and it has been only through the combined contributions of many that we have been successful."³⁶ It was a genuine team effort, with increasing reliance on automated welding technology. The virtuoso performances of the individual welder, plying his torch with sparks flying around his visored head, became an anachronism. In the case of the big bulkhead domes, the gore sections were joined two at a time while held rigidly by vacuum chucks in a precision-contoured welding jig. The welding torch, part of an automatic power pack, moved along an apparatus called a skate track, which was mounted on the exterior surface of the gores. Inchng upward at a carefully geared speed, the automatic power pack "remembered" each detail of the three-step welding operation; trimming, welding, and x-raying in sequence. Each program for the automatic power pack evolved from elaborate trials on test panels; checking and rechecking the accuracy of the trim procedure; precise current, arc voltage, and welding speed for the torch head; and quality of the x-ray. A technician rode along on the track to monitor the procedure or stop it if necessary, but the machine basically did its own thing in its own way.

The tank cylinder walls posed a far different set of problems. Each wall was machined, formed, and assembled by many different manufacturing methods; each varied because of the stresses of movement from one industrial site to another, and exposure to different influences of heat and climate. One of the most difficult aspects originated in the initial

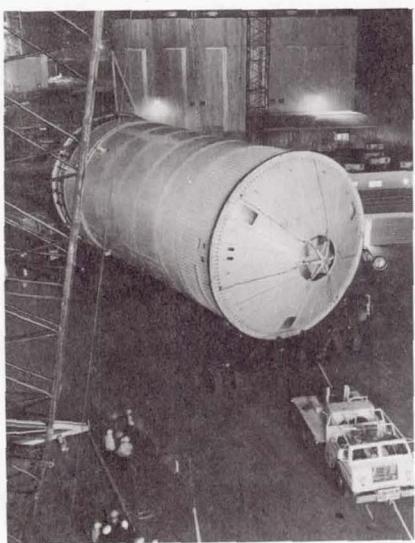
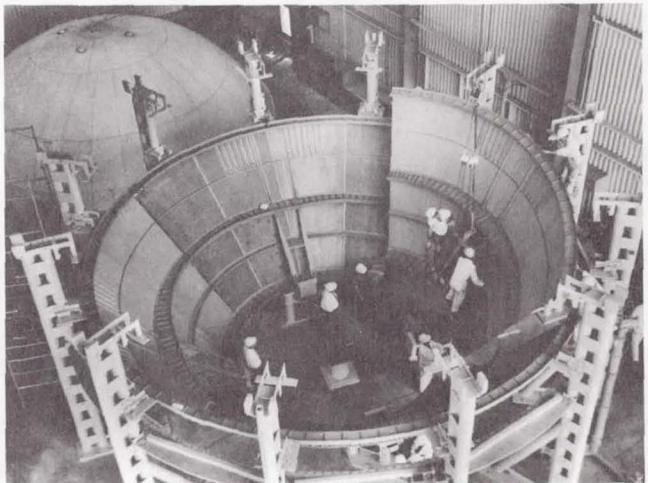
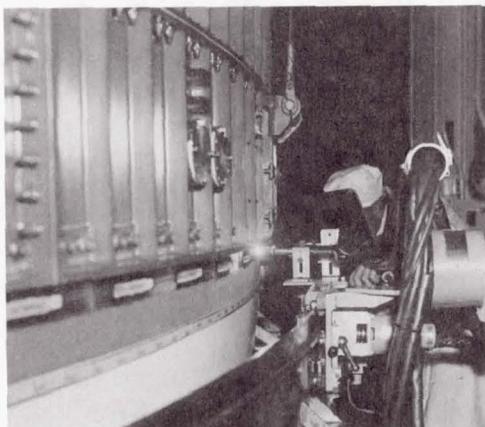
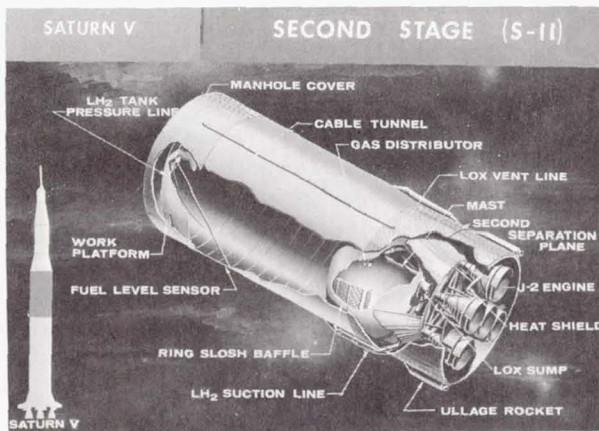
THE LOWER STAGES: S-IC AND S-II

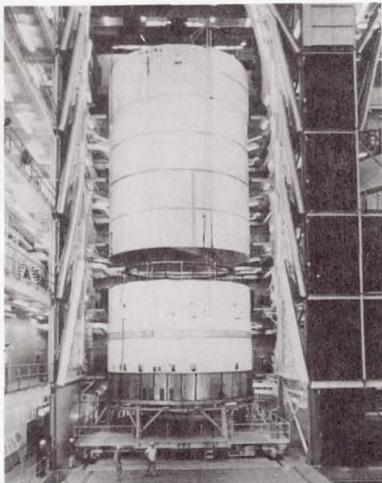
fabrication process. Each of the four cylinder sections was machined as a flat piece, then contoured to shape and welded together, with different stress factors from one completed cylinder to another. Before each welding operation, technicians reminded themselves that the cylinders were seldom true circles with nice flat surfaces for welding. During one of the first attempts to weld two cylinders together, 80 percent of the job was complete when the remaining section suddenly ballooned out of shape—the result of heat buildup and increasing stress from distortion. Exasperated specialists brainstormed the aggravating phenomenon, and tried to come up with a suitable “fix” for the problem. As a result, all the weld parameters had to be revised to include different tooling and new procedures using a series of “tack welds” evenly spaced around the circumference followed by three more passes using two skate welders operating simultaneously 180 degrees apart.

One of the most trying welding jobs in the whole operation was the joining of the forward LH₂ bulkhead to the uppermost LH₂ tank cylinder where the mismatch could be no more than 0.69 millimeter. Time after time, weld defects or mismatches occurred. Each reject required time-consuming efforts to cut open the weld, realign the pieces, and start over again. Delays at this step began to disrupt the whole program and raised the specter of late deliveries and slips in the launch schedule.

Late in 1966, a combined trouble-shooting committee was set up and jointly chaired by Werner Kuers, of the Manufacturing Engineering Laboratory at MSFC, and Ralph Ruud, executive vice-president of North American's Space & Information Systems Division. This joint approach to solving severe production problems was reflected down through the ranks, with contractor and NASA technicians working shoulder to shoulder in searching for answers. Among other things, the existing humidity conditions in the manufacturing area were reduced from 50–60 percent to only 30 percent to enhance the probability of better weld quality. An environmentally controlled, clean-room atmosphere was established by hanging huge canvas curtains in one corner of the assembly building. Personnel had to pass through a double-door airlock to get in and out of the welding area; they were required to wear white, lint-free smocks and gloves as well as step through an electric shoe brush machine to remove dirt picked up from the floor outside. Inside the clean-room area, workers continually mopped the epoxy floors to keep them free of moisture and extraneous particles; no smoking or eating was permitted in the area, and adjacent walls were painted a stark white to remind everyone in the vicinity to “think clean.”

The Kuers-Ruud team recommended a major change in the welding procedure itself. North American welding engineers had been using their own “skate” system with the welding tool moving around the periphery of the stage. The new “rotary” method, based on prior MSFC experiments and previous applications in production of the S-IC stage,





The S-II stage of the Saturn V is shown in the cutaway drawing at top left; at top right, gores are being applied to bulkheads at North American's Seal Beach facility; above, left, the automatic welding machine makes its slow circuit around the big second stage, carefully monitored by a technician. Above, right, one of the early S-II stages nears completion as the liquid hydrogen tank is lowered onto the liquid oxygen tank and their common bulkhead. Left, the final segment of an S-II stage thrust structure is lowered into place. Below, left, a completed S-II stage rolls out of the Seal Beach facility during the night shift. Below, right, an S-II stage is hoisted into the test stand at the Mississippi Test Facility.



STAGES TO SATURN

consisted of the welding tool remaining stationary while the bulkhead and tank cylinder turned on a large, motorized table. Advantages accrued from the enhanced stability of the trim and weld head, better overall control of the process, and ease of operation because bulky cables and miscellaneous equipment could be kept in one spot and not hauled around the work floor. New techniques for alignment, with adjustable screws spaced every few centimeters along alignment jigs, permitted nearly perfect match of the bulkhead and tank cylinder.

With manufacturing specifications of these magnitudes, North American experienced many long months of frustration until processes were completely under control. Not until January 1968 did the Space and Information Systems Division (S&ID) succeed in performing an error-free weld for the bulkhead-to-cylinder joint—accomplished in the buildup of S-II-9. By that time, there were only a half dozen stages left to produce. The previous stages had gone out the factory door with histories of shortcomings and corporate frustrations of considerable scope. The technical complexities of the S-II help explain the rash of problems encountered during its manufacture and test and served to highlight the trauma of NAA and S&ID's management under fire from NASA and from MSFC.³⁷

CRISIS AT SEAL BEACH

As the weight of the Apollo payloads relentlessly climbed during the early 1960s, NASA engineers redoubled efforts to lighten the stages. To get one more kilogram of payload, the laws of orbital mechanics required that 14 kilograms be cut from the S-IC; or four to five kilograms from the S-II; but only one from the S-IVB. The S-IVB stage was already in production when the weight problem became acute—it was too late to slice anything from that stage, where the advantage was greatest. Trying to scrape 14 kilograms out of the S-IC to save 1 kilogram of payload just was not feasible in terms of time and effort. That left the S-II. As the second stage became a more finely honed and thin-shelled vehicle, the balance between success or failure became more delicate. This was especially true when welding the large, thin tank skins of the S-II stage.³⁸

Manufacturing challenges such as reducing stage weight and the unusually long welding runs were not the only situations that escalated the S-II's troubles. Another persistent problem, for example, centered on the insulation for the LH₂ tank. MSFC technical monitors became increasingly concerned during the spring of 1964 and reported "considerable difficulty" in perfecting adequate LH₂ tank insulation; the growing problem crept up unawares, so to speak, and was reported with a note of surprise at MSFC. "The S-II stage insulation concept for vehicles 501, 502, 503 and to a somewhat lesser extent for S-II [ground-test vehicles] has not been fully qualified as of this date," read a memorandum dated 2

THE LOWER STAGES: S-IC AND S-II

June 1964. The memo candidly added, "This fact was discovered by Marshall personnel and came as quite a shock to S&ID management and needless to say, MSFC." The memo noted a number of anomalies, chief of which was the debonding of the nylon outer layer from the honeycomb material underneath when exposed to a simulated flight environment. The insulation difficulties became symptomatic. More serious production troubles appeared starting in October 1964, when burst tests revealed welded cylinder specimens lower in weld strength than anticipated. Then, on 28 October 1964, the first completed aft bulkhead for the S-II-S ruptured during a hydrostatic proof test, although at a lower pressure than specifications dictated. The fault was traced to a previous repair weld, done by hand, along a recirculation system service plate. While welding of a replacement bulkhead proceeded, a design change eliminated the welded service plate, making it an integral part of the bulkhead gore.³⁹

The continuing snags involving the S-II began to cause worry lines in the brows of managers at MSFC and Headquarters; in particular was the need to get the first S-II flight stage, S-II-1, out the door at Seal Beach, tested, and delivered to Cape Kennedy for the first Saturn V launch, AS-501, in 1967. Production troubles with the S-II ground-test stages by late 1964 and early 1965 threatened the S-II-1 so much that MSFC's director, Wernher von Braun, proposed a reworking of the whole S-II test program to make up some of the slippages. Major General Samuel C. Phillips, from his vantage point as Director of the Apollo Program in Washington, concurred and set in motion a series of shortcuts in the spring of 1965 to put the S-II schedule back in shape. Specifically, NASA decided to cancel the dynamic test stage (S-II-D) and, instead, use the S-II-S for this purpose after its structural tests. This decision greatly relieved both manufacturing and assembly pressures on flight stages at Seal Beach and permitted use of S-II-D hardware in follow-on stages. Further, the "all-systems" test stage bypassed its scheduled tests at Santa Susana and was scheduled for direct delivery to MTF. Meanwhile, the S-II-F facility checkout stage was scheduled to bypass MTF (where the all-systems stage would be used for facility activation purposes) for delivery direct to the Cape. There, the S-II-F would be pressed immediately into service to give Launch Complex 39 a thorough and complete checkout before the first flight stage arrived. In addition to relieving pressure on the schedule, these changes netted a savings of \$17 million.⁴⁰

Following these early deviations, the S-II program appeared to be proceeding well until MSFC decided in May to freeze the configuration of the S-II. Explaining the decision, Arthur Rudolph, Saturn V Program Manager, said that because production hardware was in the process of fabrication, engineering change activities on vehicles and ground support equipment should be frozen to the "present baseline configuration."

STAGES TO SATURN

Henceforth, only "absolutely mandatory" changes would be tolerated.⁴¹ During the spring and summer, there was reason to be encouraged by the progress on the S-II: successful battleship tests at Santa Susanna Field Laboratory, and accelerating work on the electromechanical mockup (the progress in the latter case owed a great deal to the addition of a third work shift, with each shift putting in six days a week).

Welding continued to be troublesome. Early in July, the Space and Information Systems Division (S&ID) began preparations for making the first circumferential welds on the S-II-1 (destined to be the first flight-rated stage). After completing the operation on 19 July, the weld was found to be faulty and repairs stretched into the first week of August before additional work on the S-II-1 could be started.⁴²

Then the first incident in a chain of misfortunes occurred that created one of the most serious times of trouble in the development of the Saturn V. On 29 September 1965, the S-II-S/D (structures-dynamic-test stage) ruptured and fell apart during a loading test at Seal Beach. Destruction of the stage transpired during a test to simulate the forces acting on the stage at the end of the S-IC boost phase. MSFC quickly organized an ad hoc group to determine the reasons for the accident, tagging it with a rather dramatic title, the S-II-S/D Catastrophic Failure Evaluation Team. Additionally, Marshall added a Debris Evaluation Team to help pinpoint the component that caused the failure. While the Catastrophic Failure Evaluation Team started sifting reports, Colonel Sam Yarchin, the S-II Stage Manager, instructed the people at Seal Beach to untangle the twisted metal debris in the test tower and lay it out in orderly fashion inside a guarded enclosure for minute examination by the debris evaluation team. It was eventually determined that the point of failure had been in the aft skirt area at 144 percent of the limit load. Even though considerable data had been accumulated on this particular test and earlier tests, the loss of the stage left a void in the planned vehicle dynamic tests at Huntsville; the test program was juggled around to use the S-II-T stage instead, following static testing at MTF.⁴³

The loss of S-II-S and continuing difficulties with the S-II at Seal Beach caused increasing consternation at MSFC. When the president of North American, J. L. Atwood, visited von Braun in Huntsville on 14 October, he found an indignant mood prevailing at Marshall. Brigadier General Edmund F. L. O'Connor, Director of MSFC's Industrial Operations, provided von Braun with some background data that included the following judgment: "The S-II program is out of control. . . . It is apparent that management of the project at both the program level and division level at S&ID has not been effective. . . . In addition to the management problems, there are still significant technical difficulties in the S-II stage. . . ."⁴⁴ Obviously concerned, von Braun extracted promises from Atwood to put both a new man in charge of the S-II program and a

THE LOWER STAGES: S-IC AND S-II

senior executive in a special position to monitor the plethora of technical delays and manufacturing problems.⁴⁵

In an October letter to Harrison Storms, the president of S&ID, General O'Connor started with a friendly salutation ("Dear Stormy") and ended with assurances that MSFC wanted to help wherever possible to get the S-II program back on track. In between, the general minced no words. He pointed out that the breakdown in the S-II program reflected poorly on both S&ID and MSFC's management ability. O'Connor pointed a stern finger at S&ID, remarking that he was "most apprehensive" about the entire S-II program. "The continued inability or failure of S&ID to project with any reasonable accuracy their resource requirements, their inability to identify in a timely manner impending problems, and their inability to assess and relate resource requirements and problem areas to schedule impact, can lead me to only one conclusion," O'Connor declared, "that S&ID management does not have control of the Saturn S-II program."⁴⁶ The chief of Marshall's industrial operations also conveyed his worry about the troublesome stage to the upper echelons of NASA management. Reviewing the problems during the annual program review at Headquarters in November, O'Connor noted managerial and technical shortcomings at North American and said that MSFC had "caused changes to be made in management; some people have been moved." In spite of help from the R&D operations laboratories at MSFC, problems in welding, inspection, insulation, and component qualification still existed, and as a result, the first S-II flight stage was more than three months behind schedule. "It is my opinion that program management at North American is perhaps the principal shortcoming of the entire S-II program," O'Connor said.⁴⁷

The upshot of this administrative turbulence was the dispatch of a special "Tiger Team," headed by General Phillips, from the Apollo Program Office to North American. The Tiger Team appellation apparently came out of Phillips's Air Force experience—a special, ad hoc investigative group dispatched to dig into a problem area and come up with specific recommendations to solve the issues. As a later Associate Administrator for Manned Space Flight, Dale Myers, commented, "There is a need to terrorize the contractor once in a while." The result of that visit to North American was the soon-to-be famous Phillips report, which ripped into the company's management, not only on the S-II matter, but on the spacecraft as well.⁴⁸

The impetus for this penetration of North American was a byproduct of a meeting of the President's Scientific Advisory Committee (PSAC), which convened at the Manned Spacecraft Center in Houston on 15 October. Since a covey of high-level NASA executives was attending, Phillips took advantage of the situation by assembling a select group for an intense one-hour session following the PSAC sessions. The partici-

STAGES TO SATURN

pants included George Mueller, George Low, and Joe Shea from Headquarters, along with Eberhard Rees from MSFC. The issue was North American's performance on the S-II. Rees briefed the group on plans to send "a group of selected experts from MSFC" to check on S&ID's operation on the S-II. The Marshall group, scheduled to leave on 18 October, was headed by Colonel Sam Yarchin, the program manager at Huntsville. Phillips wanted more than that. Rees reported that aside from MSFC's own S-II sleuths, Phillips wanted to take a close look at the entire S&ID operation "after Yarchin's committee has done some spade work." Phillips advocated a special survey team composed of top management from both MSC and MSFC; it was agreed to consider the matter in detail when von Braun visited Washington a few days later.⁴⁹

On 27 October, Associate Administrator Mueller wrote to Lee Atwood advising him of what was coming. Mueller noted their mutual concern that the Apollo program should stay on course to a successful conclusion, but stressed severe problems in the rate of progress for both the S-II stage and the command and service modules (CSM). The purpose of the Phillips visit was to identify "those actions that either or both of us should take." General Phillips took Joe Shea from NASA Headquarters and Rees and O'Connor from MSFC. The group went to North American on 22 November and their report was due before Christmas.⁵⁰

The "Phillips report," as it became known, was dispatched to Atwood over Phillips's signature on 19 December 1965. Briefly, Phillips told Atwood, "I am definitely not satisfied with the progress and outlook of either program. . . . The conclusions expressed in our briefing and notes are critical." The overall report was a thorough analysis of S&ID operations with various sub-teams investigating management, contracting, engineering, manufacturing, and reliability-quality control. Including Yarchin's "spadework" on the S-II, completed in early November, the thick document represented an almost unrelieved series of pointed criticisms of S&ID. Phillips offered one small ray of hope: "the right actions now can result in substantial improvement of position in both programs in the relatively near future."⁵¹ At this crucial juncture, Arthur Rudolph, head of MSFC's Saturn V Program Office, concluded that the S-II should not be starved for funds in the midst of its vicissitudes, and began massive infusions of dollars into the S-II project for overtime, increased manpower, R&D, and whatever else was necessary to see the job through.⁵²

Eberhard Rees was prepared to invoke draconian measures unless the situation at North American showed distinct improvement. On 8 December 1965, he had composed a 13-page memorandum, "Personal Impressions, View and Recommendations," based on his S&ID reviews from 22 November through 4 December. The operation was far too big and bulky, Rees observed, making it unwieldy. It needed to be slimmed

THE LOWER STAGES: S-IC AND S-II

down, and there needed to be much more awareness of progress and problems at the corporate level, which seemed to be dangerously insulated from its various divisions—S&ID in particular. In general, Rees seemed to view the situation with greater alarm than most. “*It is not entirely impossible,*” he wrote, “*that the first manned lunar landing may slip out of this decade considering, for instance, the present status of the S-II program*” (emphasis in original copy).⁵³

Rees obviously had further thoughts on this dire possibility, for on the next day he prepared an additional seven-page memorandum and attached it to the first. Marked “Sensitive, very limited MSF and MSFC Distribution,” the memo was restricted to only three copies: the original to von Braun; one copy to Phillips; one copy for Rees’s personal files. There were only a few encouraging signs at Seal Beach, he observed, and he hoped no serious dislocations would occur. Then, in a chillingly prophetic premonition, he wrote: “I do not want to elaborate on the possibility that we might lose the S-II-T stage by explosion and do heavy damage to the only test stand we have so far. But this possibility is *not* zero considering that Douglas blew up the S-IV-T on their stand with a more experienced crew and on a well broken in facility. Time delay in this case would be exorbitant.”

One of the recurrent themes of the 9 December memo involved S&ID management. Rees expressed continuing uncertainty about the ability of Harrison Storms to cope with the snowballing costs and technical hangups of the S-II program. Robert E. Greer, a Storms aide, was the man to do the job in a crunch, Rees felt, and advocated Greer to take over direction of the S-II if necessary. MSFC should keep very close watch over S&ID, Rees advised, and if their performance did not improve in 1966, then, Rees added, “*I believe NASA has to resort to very drastic measures.*” If the program still lagged, then NASA “should in all seriousness consider whether further S-II’s should be contracted with NAA-S&ID.” The bulk of S-II manufacturing facilities were owned by the government and could, if needed, be turned over to another contractor “in whom we have higher confidence.” Rees admitted that serious dislocations would develop in the interim, but the possibility should be explored. “*For me,*” he emphasized, “*it is just unbearable to deal further with a non-performing contractor who has the government ‘tightly over a barrel’ when it comes to a multibillion dollar venture of such national importance as the Apollo Program.*” (emphasis in the original).⁵⁴

With so much trauma surrounding North American’s efforts in the S-II and CSM programs, a realignment of the company’s managerial structure seemed inevitable. Already trying to get on the top of the S-II program in 1965, Storms named Robert E. Greer, a retired Air Force major general with a lean, Lincolnesque aura about him, as his special representative for the S-II. Greer had joined the company in July and took this assignment in October. By January 1966, in the wake of the

STAGES TO SATURN

Phillips report, Greer became vice-president and program manager of the S-II program. In a somewhat unusual turn of events, the man Greer replaced, Bill Parker, stayed on as Greer's deputy. Parker had joined the company in 1948, serving as S-II program manager since 1961. The company's management obviously hoped that Parker's strong background in engineering and years of experience inside the company would complement Greer's managerial skills, recently honed as Assistant Chief of Staff for Guided Missiles at USAF Headquarters.⁵⁵

In retrospect, Greer observed that the S-II program was indeed in bad shape. Among other things, he said that top management had had poor visibility, and the lateral flow of information seemed to be weak. Greer updated and revitalized his management control center to enhance management's overall conception of progress (or lack of it) in the S-II program (see chapter 9 for details on management control centers). He also instituted more management meetings, carefully structured to help the lateral flow of information, as well as garner intelligence from a broader range of sources, vertically as well as laterally. The meetings were known at North American as "Black Saturdays." The term came from Greer's earlier experience in the Air Force Ballistic Missile Division, where the commanding officer, Brigadier General Bernard A. Schriever, convened such gatherings once a month. Those attending encompassed a broad spectrum of Schriever's command. When a program director raised an issue, Schriever wanted to be able to turn directly to a staffer or engineer for an answer or advice. When Greer took over the S-II program, he also had "Black Saturdays"—except that he had them every day, limited to 45 minutes each morning; later he cut their frequency to two or three times a week.

For attendees, Greer seemed to "over-invite" people, reaching rather far down the management ladder and including various technical personnel as well. A wide variety of problems were discussed, with planners and assembly-line engineers exchanging criticisms and recommendations. The experience spotlighted a lot of otherwise hard-to-see conflicts, and certainly improved overall visibility and awareness of the S-II's development. Greer made a point of personally visiting people at lower echelons of management and engineering to enhance employee morale and accumulate additional information for himself. In any case, Greer won the respect and admiration of many of his contemporaries at North American.⁵⁶

Nevertheless, Greer's new administration took time to bring all the discordant notes of the S-II program into closer harmony. Growing restlessness spread through NASA Headquarters as the S-II-1 (the first flight stage) became the pacing item for AS-501. Early in 1966, George Mueller pointed out this dubious distinction to North American's president, but added a supportive note: "Your recent efforts to improve the

THE LOWER STAGES: S-IC AND S-II

stage schedule position have been most gratifying and I am confident that there will be continuing improvement." As it turned out, the really difficult problem became the S-II-T, which, at the present, was undergoing testing at MTF. In April, one of Phillips's envoys at MTF reported serious problems in North American's personnel; the veteran group of test people sent to Mississippi on a temporary basis had gone back to California, leaving inexperienced personnel in charge. On 25 May 1966, one fire near some LH₂ valves and another in the engine area curtailed a full-duration static test, although a successful full-duration (350+ seconds) test firing had been accomplished five days earlier. Atwood called von Braun to express his concern about the incident. Together, they discussed the probable cause, closing with discussion about different ways to expedite the program.

On 28 May 1966, a major blow to the Saturn V program came with the destruction of the S-II-T, the second S-II stage to be lost.⁵⁷ Technicians had been trouble-shooting the causes of the fires that occurred during the static tests three days earlier. With the LH₂ tank emptied, pressure checks, using helium were in progress. During prior tests, tank pressure sensors and relief switches had been disconnected, a fact unknown to the crew conducting the pressure checks, and as a result, the LH₂ tank was pressurized beyond its design limits, ruptured, and was demolished. Five men from the North American test crew were injured, and two others were hospitalized for observation. The accident occurred on Saturday during the Memorial Day weekend. Von Braun had gone to a nearby lake for some rest and relaxation, and a distraught Harrison Storms, in trying to contact von Braun at home, could only reach von Braun's wife. Storms finally contacted von Braun on Tuesday, the day after Memorial Day. "I was at the lake," von Braun explained, "and she (my wife) told me that you were on the phone with a tear-choked voice." Von Braun was both sympathetic and stern. The loss of the S-II-T underscored the managerial weaknesses at MTF, he told Storms. With so many work shifts on and off the job, it was easy to foul things up. The contractor needed more seniority and better procedural control. The next day, in a call to Robert Gilruth at Houston, von Braun remarked that he saw nothing basically wrong in the design of the S-II. Its problems could be traced to management, procedure, and human error. The MSFC director summed up his view of the S-II's agonies in a terse assessment: "The whole thing is NAA, S&ID."⁵⁸

Ripples of the S-II-T's destruction were felt in the launch schedule for AS-501; slippage in the S-II-1 flight stage had led to plans to use the S-II-T at Cape Kennedy to stack the AS-501 vehicle for systems tests and replace it later with the flight stage. Investigation of the S-II-T uncovered the presence of tiny cracks in the LH₂ cylinders near the rupture area. Inspection of other manufactured stages and cylinders in production

STAGES TO SATURN

revealed more minute cracks, leading to considerable delays in repair and modification work.⁵⁹ Now, the successful launch of AS-501 depended even more heavily on successful testing of the first of the S-II-1 flight stages; the latter left Seal Beach on 31 July for a critical series of static firing and acceptance tests at MTF. By mid-August, the S-II was set up in Test Stand A-2 for checkout prior to static firing, which did not occur until the first of December. The intervening time was filled with a series of nettling problems—"the continuous surprises that keep occurring after the stages arrive on deck at MTF," as Rees complained to Storms during one of his weekly teleconferences.⁶⁰ MSFC listed complaints on workmanship and quality control, including leaks around supposedly impervious seals; this situation led to the postponement of the first static test scheduled in late October.⁶¹

MSFC personnel found faults not only in the S-II-1 but in other stages. For example, the second flight stage, S-II-2, had been ordered back to the factory for numerous modifications and fixes. Many of the same operations had to be repeated on other components in various stages of fabrication and assembly. Managers at MSFC organized special Tiger Teams of technical and test operations personnel, dispatching them to MTF to assist in the static firing. All of this did little to cheer up the Apollo Program Office in Washington. During a year-end session of the annual program review, Phillips, still unhappy, summed up the assorted ills and tribulations of the S-II: "The performance of the contractor has not measured up to the minimum requirements of this program."⁶²

With a few perturbations here and there, including a major change in the contractor's management, 1967 was a year of contrast for the S-II. During January, Phillips reported to the Office of Manned Space Flight (OMSF) that organization and test procedures had improved at MTF.⁶³ To cope with the continuing problems at Seal Beach, MSFC sent a new Tiger Team, under the leadership of Colonel Yarchin, the S-II project manager, to the West Coast. Yarchin and 15 well-known technicians left early in January. This created questions in the aerospace press and elsewhere, about the nature and extent of North American's vicissitudes. MSFC prepared a statement as a guideline for use in answering questions raised by reporters, emphasizing the basic soundness of the S-II design, while admitting the need for MSFC's technical assistance in welding and other procedures at Seal Beach. By the end of the month, Phillips reported to the Associate Administrator that MSFC welding techniques had been adopted on the S-II. During March, a welding team from S&ID traveled to Marshall to observe techniques for reducing the frequency of weld defects in the circumferential welds of the LH₂ tank.⁶⁴

Besides the S-II program, the beleaguered management at North American was trying to cope with production problems and schedule slippages involving the command module. Concern for the CM issue

THE LOWER STAGES: S-IC AND S-II

caused the Phillips team, which descended on North American in 1965, to include more people from the Manned Spacecraft Center in Houston (who had NASA responsibility for the CM) than from MSFC.⁶⁵ Then, tragically on 27 January 1967, a flash fire in the CM during prelaunch tests at the Cape claimed the lives of astronauts Virgil I. Grissom, Edward White, II, and Roger B. Chaffee. The fire exacerbated NASA's concerns about the management structure of S&ID. The aftermath of the fire brought reworking of the CM and prelaunch test procedures and modification of many schedules. The delays, however, aided the Saturn vehicle contractors.⁶⁶ The fire also triggered further reorganization of North American, as the company continued to contend with the persistent criticism of its performance from NASA. In a series of moves announced early in May 1967, company president Atwood streamlined S&ID and drastically shuffled his management team. The "information systems," part of Space and Information Systems Division, was snipped off and spliced into the Autonetics Division at Anaheim, leaving Space Division to concentrate on the Apollo program. Harrison Storms, relieved as president of S&ID (at Downey), became a corporate vice-president, and was replaced by William "Bill" Bergen, who had only recently resigned as president of the Martin Company, an aerospace firm in Baltimore, Maryland. Bergen was given the assistance of some of North American's top executive experts. Paul Vogt, newly appointed vice-president in the Space Division, had special responsibility for improving engineering, manufacturing, and quality control. Ralph H. Ruud, an expert on materials and quality control and former corporate vice-president for manufacturing, took over as Bergen's executive vice-president. In addition, North American management at the Cape was realigned into a more unified structure reporting directly to Bastian "Buzz" Hello, who came with Bergen from the Martin Company.⁶⁷

In the meantime, delivery of the S-II-1 stage to the Cape in late January prompted cautious optimism about the overall progress for the Saturn booster; this optimism was short-lived, clouded by mounting requirements for "open work" on the stage, involving modifications to hardware that only recently had emerged from production lines. "This growth in modifications downstream all the way to the stack at KSC must be arrested," Mueller told the president of North American. "We simply must attain early definition of the work to be accomplished at the proper station and ship complete stages to MTF and KSC."⁶⁸ As an example of these vexatious problems, tiny "hairline" cracks found in S-II tankage under manufacture led to a huddle in Washington on the possibility of similar faults in the S-II-1 already stacked with other stages for the AS-501 launch. With the launch scheduled for mid-August, individuals meeting at NASA Headquarters on the afternoon of 24 May considered the possibility of missing the launch date because of the inspection work to be done on S-II-1. The top-level decision group, including Phillips,

STAGES TO SATURN

von Braun, Debus, O'Connor, Rudolph, and Yarchin came to the only safe decision: take down the S-II-1 and conduct extensive dye penetrant and x-ray inspection of the welds in the LOX and LH₂ tanks.⁶⁹ The inspection uncovered a dozen imperfections requiring careful tank repairs and burnishing of the tank walls. The original August launch date kept slipping, but other modifications were also made to the rest of the vehicle and the ground equipment. It was not the sole fault of S-II-1 that AS-501 did not leave the pad until 9 November 1967.⁷⁰

SUMMARY: S-IC AND S-II

It would be inaccurate to say that the S-IC project waltzed through its development without a stumble. Still, there were decidedly fewer traumas with it than with the S-II. The S-IC clearly profited from the close association with MSFC's own fabrication and manufacturing specialists early in the game. The use of conventional propellants like RP-1 and liquid oxygen represented a lower magnitude of difficulty in producing tanks and accessories.

North American had trouble with the S-II, at least in part, because the company had some management difficulties. In fact, the problems, had been growing many months before the crisis of 1965–1966. Von Braun's "Daily Journal" expressed concern about management shortcomings as early as 1963, citing problems in cost overruns and organization of manufacturing units.⁷¹ Moreover, the S-II program got caught in a weight-shaving program, which made working with its extremely thin-walled tanks and other lightened hardware even more difficult.

The turn-around for the S-II by 1967 resulted from the resolute, though agonizing, reorganization of North American's management. The reorganization created better visibility and more direct interaction between corporate managers and the divisions, and benefited from the streamlining of S&ID itself, and the ability of Robert Greer. Greer's combination of managerial skills and the ability to come to terms with the technical problems commanded the respect, loyalty, and performance from North American's workers at a crucial time. North American was competent to do the job; reorganization and tighter management enabled North American's capabilities to be applied more effectively.⁷²

Finally, the influence from NASA Headquarters and from MSFC was extremely significant. The thorough assessment by the Phillips team influenced North American's realignment in the right direction. Added to this was the impact of various technical teams from MSFC dispatched to Seal Beach and MTF to help solve perplexing hardware problems and operational snarls. Sometimes this was a hindrance. In Greer's opinion. Marshall's ubiquitous engineers and direction from Huntsville reached the point where North American's attempts to catch up were snarled by NASA's red tape.⁷³

THE LOWER STAGES: S-IC AND S-II

In spite of all the early predicaments in the Saturn program caused by the S-II, the Saturn V nevertheless launched men to the moon within the decade; and the S-II stage, along with other Saturn components, compiled a perfect record of successful missions.

In part, the success of such complex machines rested on new plateaus of achievement in electronic circuitry and computer technology.

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8

From Checkout to Launch: The Quintessential Computer

During World War II, the growing sophistication of weapon systems and communications equipment prompted development of test procedures to ensure that everything was in proper working order. Automatic testing, or checkout, saved time and reduced the large number of specialists who would otherwise have to be trained to do the job. In the post-World War II era, larger and ever more complex missile systems created new difficulties in testing and monitoring the internal condition of the missile. Computers were introduced not only to measure the level of fuel and oxidizer in the tanks, but also to assess propellant qualities such as temperature, stratification, and boil-off rates. Continuous monitoring of the condition of propellant machinery, missile electronics, and various internal rocket systems became significant functions of computer checkout. The Atlas, the first American ICBM, used the kind of comprehensive checkout equipment that would be elaborated in the course of the Apollo-Saturn program. Once launched, rockets like the Atlas needed precise guidance and control. Other, smaller computers and associated equipment aboard the vehicle maintained the proper course and controlled the flow of propellants. Again, the Apollo-Saturn elaborated on equipment developed for ICBMs.¹

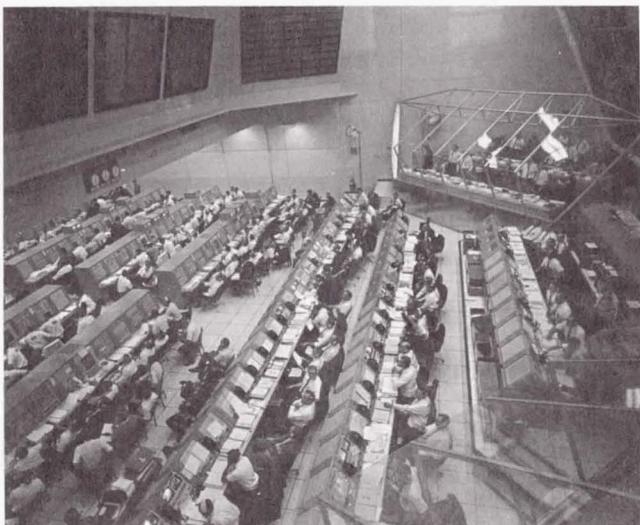
AUTOMATIC CHECKOUT

"A check-out system is considered automatic" according to one definition, "when it can, to some degree, autonomously sequence a series

STAGES TO SATURN

of measurements of equipment outputs and comparisons of these measurements against standards." A manual test system, on the other hand, required the operator to switch the equipment from one reading to a different one and to make comparisons on "go/no-go" conditions. For NASA engineers, the intricacy and enormity of measurement and comparison was evident by taking a look at the number of comparison test points in the Apollo-Saturn vehicle. Vanguard, produced by Martin, required only about 600 test points. The Apollo spacecraft, on the other hand, included over 2500 test points on the command module and the lunar module, and another 5000 on the Saturn itself. Further, these test points were checked and monitored constantly from early manufacturing checkout sequences, to pre-static-firing checkout, to post-static-firing checkout. Test points were checked scores of times in the 12–14 weeks required prior to a launch for complete checkout of the Apollo-Saturn stack at Cape Kennedy. Without computer technology, such procedures, even at the launch site, might have stretched out the checkout procedures for more than a year.² Checkout equipment and procedures went beyond the point of merely pinpointing a fault in the equipment. The automated checkout paraphernalia associated with the Apollo-Saturn program additionally incorporated a diagnosis function; computer or screen readouts would indicate to the test engineers and programmers not only that a problem existed, but also the nature of the problem, its causes, and possible solutions.³

In the evolution of automated checkout equipment, one of the most interesting problems centered on the creation of a new language. The language tapes incorporated in the computer programs had to be functional for the designer of the vehicle as well as the test engineer. Readouts on malfunctions had to make sense to persons reworking the piece of hardware that failed or had not performed properly. Obviously,



Computers and their end product devised for Saturn V—automatic checkout of flight hardware—were much in evidence at the Kennedy Space Center. This view of the control center, with row on row of computer consoles, is only one portion of the system.

FROM CHECKOUT TO LAUNCH

each of these individuals came to the language problem from a different background and with a different goal in mind. Melding two such disciplines together was not always an easy task. Earlier in the Saturn program, Marshall Space Flight Center had developed two separate languages for computer operations—one for stage testing and one for launch site operations. This situation obviously created communications problems and was complicated by the fact that each of the stage manufacturers was also using its own computer language based on the particular requirements of its own test designers and engineers. A further entanglement involved the rapid evolution of checkout programs. Test engineers were putting new demands on the computers, and these new demands as well as the style of language had to be communicated to the programmer. To arrive at an appropriate language, either the test engineer had to learn more about programming, or the programmer had to learn more about test engineering. The solution to this dilemma was ATOLL, an acronym for Acceptance Test or Launch Language, designed to bridge many of the gaps between the test engineer, the designer of the stage, and the computer programmer. Originating in late 1963, ATOLL eased confusion and helped to normalize the many functions of automatic test and checkout encountered at the manufacturer's plant, during static firing, and during operations at the launch site.⁴

In a typical test sequence a number of things happened. For example, the test engineer inaugurated the program by typing in the instructions on his console. The computer responded by reading out for the test engineer the status of the selected program. When the program was ready for running, this was indicated on the appropriate panel of the computer. The information appeared in English on either the cathode tube of the program display or on a video data terminal. Perhaps the display also included numerous options for the engineer, depending on which portions of the test he wanted to pursue at the time. If some selected part of the test required a further breakdown for the engineer's consideration, instructions could also be typed in, and the computer would respond on the display tube. When either programming difficulties or hardware problems cropped up, the computer might give the test engineer a choice of several actions: terminate the test, go back to a prior enumerated step, proceed, or some other option. Further, in the process of running the test, all the results were shown on engineering display consoles and recorded both in print and on magnetic tape. These readouts were stored and, in some instances, were correlated into previous test operations for checking at some later date. Thereafter, if an anomaly occurred, it was possible to run a check through the computer all the way back to the machine shop floor to see what discrepancies or difficulties might have occurred in the test conditions, hardware, or in the manufacturing process itself.⁵

STAGES TO SATURN

Prior to the static-firing program (and before any mating of the separate stages occurred), each Saturn stage had to pass checkout requirements. Although the final test goals were similar for each stage, the differences between stages required a "custom-tailored" test for each one. Designing a checkout system to satisfy the unique requirements of the instrument unit and each stage, and also meet integrated vehicle requirements, became what MSFC called a "major task." The Marshall group drew on its experience with the Redstone, Jupiter, Mercury, Saturn I, and other rocket programs in establishing the checkout organization.⁶

SATURN AUTOMATIC CHECKOUT

The decision to use automated stage checkout for the Saturn program rested on several factors. D. M. Schmidt, of MSFC's Quality and Reliability Assurance Laboratory, summarized them at a technical conference in New York City in 1965:

- High reliability is needed; vehicle is expensive and is man-rated.
- Truly integrated designs of stages and support equipment would reduce the number of operational problems.
- Human errors and human slowness must be improved upon.
- An engineering approach is feasible throughout design, production and test, military restraints being absent.
- The time scheduled for checkout must be used more effectively than on previous programs.
- The volume of technical data to be measured and handled is extremely large; each flight stage alone has hundreds of measuring devices aboard (perhaps as high as 1000).
- All data must be transmitted long distances on a limited number of channels. Launch pads are far from control consoles. Stage checkout must meet launch needs.
- Test and launch data must be retrieved, stored, and made available to many organizations.
- Automation increases the powers of human operators to deal with complex situations and frees them for decision-making.
- Data-handling needs are many and varied: accuracy of measurements and transmission, versatility of equipment, speed of operation, operating-time recording, failure histories, data comparisons.⁷

For the Saturn program, checkout included two distinct phases. "Stage checkout" included test sequences conducted on the individual stage during manufacturing and static firing prior to NASA's acceptance for assembly into the launch vehicle. "Vehicle checkout" included tests on the assembled launch vehicle at the launch site. A complete checkout of the stack was deemed necessary because an individual stage might function perfectly in tests that simulated interaction with other stages, but not function as well when linked together physically in the stack.

FROM CHECKOUT TO LAUNCH

Marshall's main interest was the actual stage checkout, with responsibility for final launch vehicle checkout resting with Kennedy Space Center. Originally, NASA planners envisioned repeating the stage checkout after the delivery of each stage to Cape Kennedy, but it became apparent that this scheme compromised the time and resources required for final checkout and launch. Therefore each stage received final checkout before transport to the launch site. The procedure not only made it easier to accomplish the final checkout and launch, but enabled MSFC and the contractors to deal more efficiently with problem areas at the stage test facility (where specialized personnel and equipment were present). This concept paid off on the first three Saturn V vehicles when stage checkouts uncovered 40 serious defects; these flaws would have gone undetected had the stage checkout depended only on procedures and facilities available at the launch site.⁸

Each booster stage was subjected to a post-manufacturing checkout, a checkout prior to static-firing tests, and a post-static-firing checkout. Static firing, the most dramatic test, tested the propulsion systems during actual ignition and operation. Checkout featured a "building-block" sequence, common to all stages, with variations as necessary for an individual stage. A typical sequence began with an independent electrical system test and was followed by a simplified rundown of the launch sequence. Next, other systems were run in succession; guidance and control system tests; a second launch sequence run with these and other electrical and propulsion systems tested; completion of ancillary system tests; an all-systems test; and, finally, a "simulated flight" test, including ignition and a duration burn.⁹

The Saturn stages and the associated checkout equipment for each were developed simultaneously with the goal of an integrated design of the vehicle and its ground equipment. Some of the vehicle's mechanical equipment—such as sensing equipment for checkout of a number of items operated by fluid, as well as fluid management subsystems—did not lend themselves to checkout with digital computers. Design engineers succeeded in developing suitable checkout equipment for the electrically actuated and measured equipment so that the great majority of stage checkout tests would proceed automatically. The Saturn I vehicles offered the first experiences in stage checkout for Saturn class vehicles. Whereas the vehicle SA-1 required manual checkout, by the end of the Saturn series automatic equipment controlled over 50 percent of the tests. The automatic capability improved during the S-IB vehicle series, and checkout of the Saturn V stages, including the instrument unit (IU), was about 90 percent automated.¹⁰

Checkout equipment for S-II and S-IVB stages of the Saturn V was developed by the stage contractors under the direction of MSFC. For the S-IC, Marshall collaborated with Boeing in developing the automated equipment, because the first S-IC stages were fabricated in MSFC shops

STAGES TO SATURN

at Huntsville. Boeing employees trained on the first two S-IC stages at Huntsville, then checked out later stages at Michoud. For the IU, checkout equipment previously developed by Marshall for the Saturn I was utilized, with IBM in Huntsville assuming responsibility for later work. The S-IC stage and the IU checkout operations both utilized the RCA-110A digital computer. NASA had already decided to use the RCA-110A for launch control, so the interfaces with the S-IC and IU were compatible. In contrast, the S-II and S-IVB stages relied on the CDC-924A computer, supplied by Control Data Corporation. The design of this computer offered added flexibility for checkout of the two upper stages, which utilized liquid hydrogen as fuel, mounted the J-2 engine, ignited at high altitude, and included several unique design features. Also the CDC-924A, which was based on later-generation computer technology, offered added test functions.¹¹ The Saturn program also relied heavily on the "Saturn V Systems Breadboard," a facility located at MSFC. The breadboard incorporated both mechanical equipment and electronic simulation and was used for wringing out the checkout procedures and launch control operations at the Cape.¹²

Not everyone was happy about the escalating preeminence of automation. Many of Douglas's own people opposed the ubiquitous computer. "In fact," an automation expert at Douglas admitted, "the company was surprised to find that its equipment took the automation more readily than did its engineers."¹³

In the pre-Saturn days of rocket and missile operations, many checkout procedures were performed manually and worked well with complex vehicles like the Thor-Delta. Douglas engineers used manual checkout techniques for the earliest S-IV stages; pre-checkout, acceptance firing, and post-checkout required a total of 1200 hours per stage. Veteran "switch flippers," who for so long scanned gauges and dials, flipping the right switch in a critical situation, had been vital links in the overall loop. They were now replaced by ranks of gray-enameled computers. For checkout procedures on the Saturn V third stage, the S-IVB, fully automated techniques replaced the manual checkout for the first time. Although the magnitude of testing rose by 40 percent per stage, the new automated systems reduced the checkout time to about 500 hours total. H. E. Bauer clearly remembered the occasion when men and the new machines first confronted each other. "One seasoned switch flipper came into the blockhouse after the equipment was installed; he watched the blinking lights, the scanners, the recorders—everything was working automatically, heaving out wide and endless runs of data printouts. . . ." The man balefully surveyed the mechanically throbbing interloper and growled, "It's the Gray Puke!" It was not an isolated reaction. As Bauer recalls, the ghastly name stuck and became part of the permanent lexicon associated with the S-IVB stage.

Even with mechanical drones like the Gray Puke usurping the

FROM CHECKOUT TO LAUNCH

human role, the man-behind-the-machine could still display some semblance of individuality. Consider, for example, the case of the petulant computer-printer—when the machine apparently took umbrage during the automatic checkout sequence in preparation for an acceptance firing. The moment of truth for the test arrived—the signal to fire. After uncounted hours of preparation, hundreds of workers now stood by to observe the climactic moment of ignition. In the crowded blockhouse, all eyes focused on the rows of computers and monitor screens displaying their last fragments of information. Finally, the test conductor typed in his “request” to start the terminal countdown for static firing. The computer whirred, and the automatic typewriter responded with a singular reply, “Say please.” Startled, the test conductor concluded he had made a typing error, and repeated his original message more carefully. The balky computer was not to be denied. “Say please,” it insisted. At this point the crowd in the blockhouse began stirring restlessly. The loaded S-IVB, readied for firing, remained poised nearby with thousands of gallons of liquid oxygen and liquid hydrogen primed for detonation. People were getting tense. Reasonably certain he was only working against a faulty firing tape, the test conductor quickly decided to make one more try, rather than put it into discard and risk more precious time to put a replacement tape into operation. So once more, he entered into the machine his humble request to fire, with a polite notation at the end: “please.” This time, there was no problem. “This is your programmer,” the machine chattered back, “wishing you good luck.” And with a roar, the rocket ignited.¹⁴

GUIDANCE AND CONTROL

With computer data accumulated for each stage and subsystem, the collected information was not only utilized for vehicle checkout at the Cape, but also for the launch and for guidance and control during the mission.

After years of research and development on the individual stages, involving thousands of workers and millions of man-hours, most of the responsibility for the six-hour flight of a Saturn V devolved on a piece of equipment known as the instrument unit—the “IU.” A thin, circular structure, only 1 meter high and 7.6 meters in diameter, the IU was sandwiched between the S-IVB stage and the command and service modules. Packed inside were the computers, gyroscopes, and assorted “black boxes” necessary to keep the launch vehicle properly functioning and on its course.

Historically, the problems of traveling successfully from point A to point B on the Earth’s surface depended on some form of visual references, such as tall trees, mountains, or some other easily sighted

STAGES TO SATURN

landmark. Longer journeys overland, where familiar landmarks were unavailable, and extensive sea voyages, out of sight of any landmarks at all, came to rely on guidance instruments such as compasses and the astrolabe. Rocket vehicles, on the other hand, with their extremely high speeds, altitudes, and long-range capabilities, came to depend on advanced guidance systems coupled with control systems that were essentially automatic.

The Saturn rockets relied on inertial guidance, involving a rigid member within the vehicle. This member, an integral element of the guidance package, was oriented and held unchanging by means of gyro units, gimbal systems, and servomechanisms. Additional equipment tied into the inertial guidance unit contained all the data needed to sense the distance traveled by the vehicle and the deviations from the desired path and to control the vehicle in accordance with its computer memory.¹⁵

The guidance and control techniques applied in the Saturn program involved many problems. Successful solutions were reached partly through new research and development and partly through the use of proven techniques and hardware adapted from existing systems. The Saturn digital computer and the data adapter stand out as new developments. The inertial platform, on the other hand, was a result of concepts and hardware worked out in the late 1930s and early 1940s in Germany.

Inertial guidance rested on the technology of precision gyroscopes. Gyroscope technology progressed considerably during World War I, based on requirements for controlling the gunfire of long-range naval guns at sea. During the 1920s and the 1930s, further development of gyroscopic systems involved aircraft applications, which included rate-of-turn indicators, the artificial horizon, and the directional gyro. Despite the remarkable advances in aviation guidance instruments for navigation and "blind flying," instrument precision and response rates were inadequate for application in high-speed rocket vehicles. New developments were required in gimbal systems, servomechanisms, electronics, computers, and other equipment leading to inertial guidance systems for rockets and missiles. An intensive effort to perfect such hardware occurred in the late 1930s and during World War II, particularly through the work accomplished in missile research by the von Braun team in Germany. C. Stark Draper, a leading postwar specialist in the field of guidance and control, acknowledged the contributions of the von Braun team in no uncertain terms. "Beyond doubt," he declared, "credit for the realization of inertial guidance belongs to the Peenemuende group of German scientists who developed the V-2 ballistic rocket missile."¹⁶

In the A-4 missile (the V-2), a pair of gyros was used in a guidance system known as the LEV-3; one free gyro controlled roll and yaw, one controlled pitch, and a tilt program put the missile into the proper angular attitude after its vertical launch. The LEV-3 employed a gyro-type accelerometer as a propulsion cutoff system, the device being preset

FROM CHECKOUT TO LAUNCH

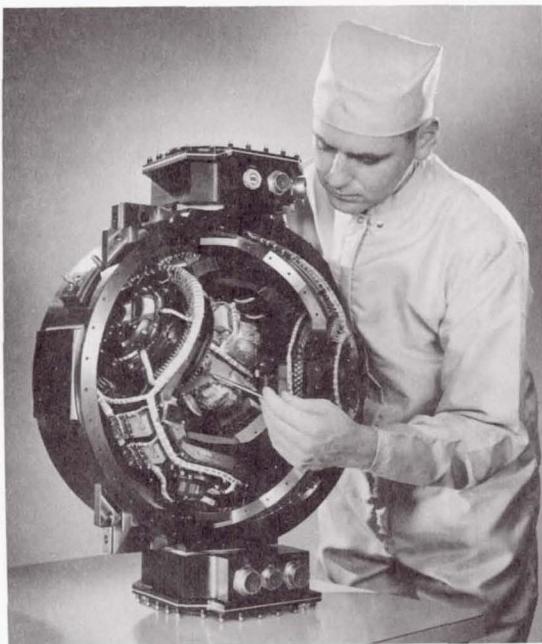
to cut off the engines when the missile reached a predetermined velocity. With this pair of two-degree-of-freedom gyros, the LEV-3 was a three-axis-stabilized platform (an inertial guidance concept), the result of very high quality research and development in precision machinery, materials, advanced theory, and innovative design concepts. Moreover, the whole system was manufactured in quantity.¹⁷

The LEV-3 was a milestone in the art of guidance and control for rockets; it established the basic design concepts for the inertial guidance concepts that followed during V-2 development in wartime Germany.¹⁸ One of the most significant developments occurred through the work of Fritz Mueller, at Kreissel Geralte GMB. H. This was the SG-66, a three-axis platform with advanced accelerometers and integrators. Boasting much improved precision and accuracy, it was coming into production for use in German missile systems when the war ended. After the von Braun group moved to Huntsville, Mueller directed further refinements of advanced V-2 guidance concepts developed at Peenemuende which ultimately resulted in a far superior piece of equipment. The new variant featured an air-bearing system for three single-degree-of-freedom gyros integrated in a gimbal-ring structure; this yielded a three-axis stabilized platform. Further work by other Peenemuende veterans and an analog guidance computer devised with American researchers at the Redstone Arsenal culminated in the ST-80, the stabilized platform, inertial guidance system installed in the Army's 1954 Redstone missile. Prior to launch, the intended flight profile was fed into the missile's computer guidance program. During flight the ST-80 combined with the guidance computer kept the missile on its preplanned trajectory with no external guidance influences.¹⁹

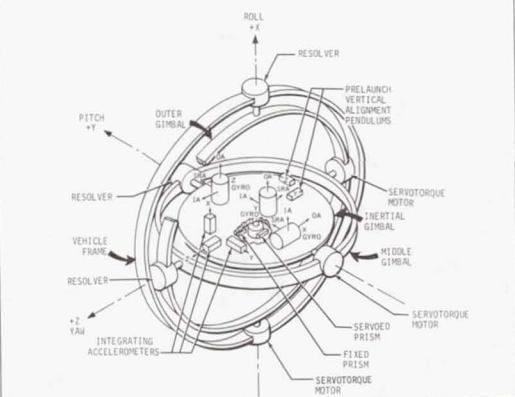
The ST-80 of the Redstone evolved into Jupiter's ST-90 (1957); both were turned over to the Ford Instrument Company for manufacture. When the Saturn I began to evolve, the Army Ballistic Missile Agency (ABMA) guidelines called for the use of proven and available hardware wherever possible. For example, the early Satellites incorporated the ST-90 stabilized platform with an IBM computer, the ASC-15 model, adapted from the equipment used on the uprated Titan II.²⁰ At a later date, as other vehicle test milestones were passed, a different guidance and control unit was proposed. This new unit, the ST-124, was an improved inertial guidance platform intended for the Saturn V's complex and long-term orbital mission.

EVOLUTION OF THE IU

The instrument unit (IU) evolved as an "in-house" project at Marshall Space Flight Center and was based on the guidance expertise



PLATFORM GIMBAL CONFIGURATION



The ST-124 inertial guidance platform is given a technical check (left); above is a schematic of its systems.

accumulated from the V-2, the Redstone, and subsequent vehicles developed by the von Braun team.

Beginning in 1958, work on the IU was concurrent with the Saturn I. On 15 June 1961, the mockup of the IU was completed at Huntsville and scheduled to fly in the Block II series of the Saturn launch vehicles.²¹ For the Block I vehicles with dummy upper stages, guidance and control equipment was packaged in canisters located at various points in the adapter area atop the S-1 first stage of the Saturn I. This equipment included telemetry, tracking, and other components, such as the ST-90 guidance platform and a guidance signal processor. Plans called for an additional canister to carry the ST-124 platform as a "passenger," thus beginning its sequential tests and qualification as the active guidance component for later Saturn I, Saturn IB, and Saturn V flights.

MSFC intended to make the ST-124 an increasingly active system for SA-5 and subsequent vehicles and to link it with an IBM computer. SA-5 was the first of the Block II vehicles of the Saturn I series. It featured a live S-IV upper stage and a separate vehicle segment, located above the S-IV, for guidance and control (to be known as the IU). Standing about 1.5 meters high, the cylindrical IU section contained four package bays that had been shaped in the form of large tubes and cruciformly joined in the center. This new structural element was

designed for greater flexibility and permitted modifications between launches, if so dictated by results of the previous launch and changing test requirements. The four tubular segments contained the ST-90, the ST-124, the telemetry equipment, and the power and control package.²²

With the flight of SA-9, the Saturn I vehicles began carrying a new type of instrument unit, which resembled the equipment later applied in the Saturn IB and Saturn V flights. In the earlier design, the tubular package bays were pressurized and surrounded by an inert gas as a means of environmental control to cope with the problems of heat. In later instrument unit design, however, equipment was mounted on the walls of the cylindrical segment. With this design the cylindrical unit was not pressurized, and the external style of environmental control by inert gas gave way to a revised system. Elimination of the pressurized tubular sections and other simplifications not only reduced the weight of the instrument unit, but also reduced the height of the segment by half, thereby improving the structural and flight characteristics of the late Block II launch vehicles. Introduction of the improved instrument unit marked growing participation of contractors, including the Bendix Corporation, for the ST-124, and IBM, who assumed increasing responsibility for the instrument unit segment and various guidance components.²³

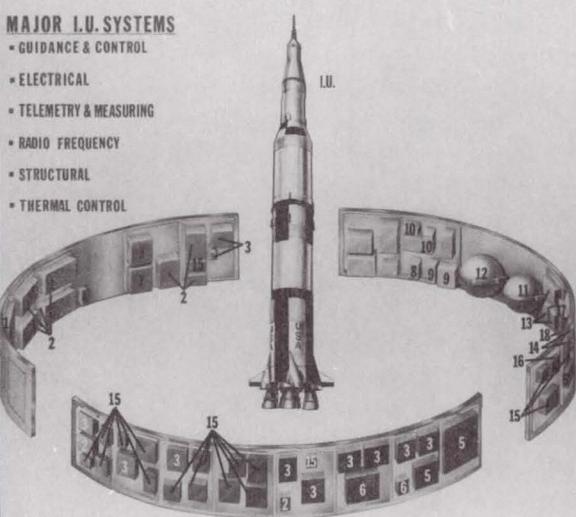
The major role of IBM as the principal manufacturer for the instrument unit began in February 1964. The company was named prime contractor for both the Saturn IB and Saturn V versions of the IU and was responsible for building, testing, and shipping the instrument unit to Cape Kennedy. With MSFC retaining primary responsibility for the buildup of the first four units and the first four flights of the Saturn IB, IBM was able to ease into its work. For the first instrument unit, 80 percent of the hardware was classed as government-furnished equipment; this was reduced to 10 percent when IBM took over for the fifth unit. The instrument unit for the Saturn V was essentially the same as the model for the Saturn IB, because the evolutionary process of development and manufacturing was intended to give the Saturn V a proven piece of equipment with as few changes as possible.²⁴

Unlike most major launch vehicle components, which were manufactured elsewhere around the country, the instrument unit was produced in Huntsville. IBM made a major commitment in setting up complete research and development facilities, engineering offices, and production facilities in the city's Research Park. Although the company started with only a sales office building in Huntsville in 1962 and originally assumed most of its work would be done in New York, the scope of work implied a need for new facilities, and IBM decided on a complex in Huntsville. By 1964, IBM completed a manufacturing building in Huntsville's Research Park, and the company site included four major buildings, representing a \$14 million investment with a work force of 2000. Clinton H. Grace, the facility manager at Huntsville, was a

SATURN IB/V INSTRUMENT UNIT

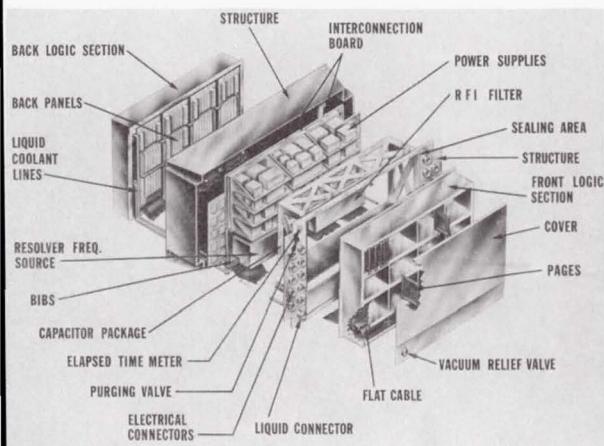
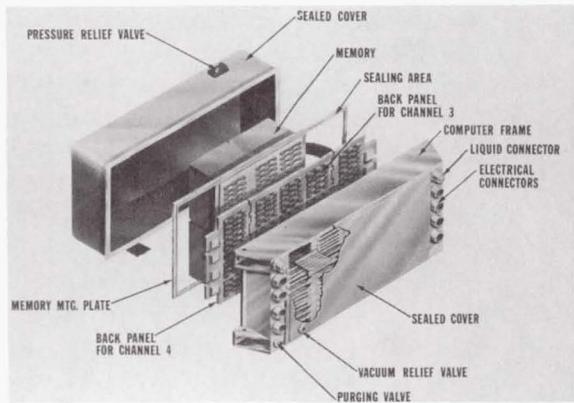
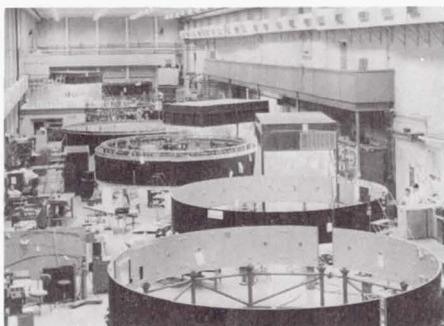
MAJOR I.U. SYSTEMS

- GUIDANCE & CONTROL
- ELECTRICAL
- TELEMETRY & MEASURING
- RADIO FREQUENCY
- STRUCTURAL
- THERMAL CONTROL



1. ENVIRONMENTAL CONTROL SYS.
2. ELECTRICAL POWER SYS.
3. MEASURING SYS.
4. CONTROL ACCELEROMETERS
5. CONTROL COMPUTER SYS.
6. EDS
7. RADAR ALTIMETER
8. C-BAND RADAR
9. AZUSA SYS.
10. MINITRACK SYS.
11. ST-124-M PLATFORM
12. PLATFORM AIR SUPPLY
13. PLATFORM ELECTRONICS
14. GUIDANCE COMMAND SYS.
15. TELEMETRY SYS., SWITCH SELECTOR, GUIDANCE COMPUTER
16. DATA ADAPTER

The instrument unit used in Saturn IB and Saturn V is shown in component detail in the drawing at left; below, left, in IBM's Huntsville facility, IUs are joined together and instrumented. Two of the key components in the IU are the launch vehicle digital computer (below, right) and the launch vehicle data adapter (bottom, left). At bottom right, this completed IU is undergoing rigorous checkout and test before shipment to KSC. Both IBM and MSFC engineers are monitoring the checkout.



FROM CHECKOUT TO LAUNCH

dynamic force in both the organization and buildup of the IBM complex and won high praise from Wernher von Braun. Speaking at the dedication of the IBM facility in 1965, von Braun commented, "In this project, a saying has developed at Marshall Center, 'When you're in trouble, say 'Grace'—and Grace will take care of your problems.'"²⁵

The ground rules for the design, research, and development of the IU came out of MSFC, and these concepts carried over into the production models delivered by IBM. With cost constraints and tight schedules limiting the number of test flights, the number of measurements for each flight was expected to be quite high and to vary considerably from one flight to another. For this reason, flexibility for the instrument unit had a high priority and designers emphasized a modular approach as means to provide both flexibility and ease of servicing. Another strongly emphasized feature was reliability; a key factor, particularly because the Saturn program was geared to manned launches. In addition, liability was enforced by the high cost of each vehicle and limited test flights, which naturally produces a reluctance to fly exotic, untried, hardware. As James T. Powell, of Marshall's Astrionics Laboratory stressed, "We simply cannot afford the time or money to launch additional vehicles to obtain data lost by instrumentation equipment failures. This has led to a rather conservative approach to system design." Some innovations, such as new modulation techniques or micro-miniaturization, might turn out to be "equivalent in importance to the invention of the wheel," Powell remarked, but would not be used in the Saturn program until they had undeniably demonstrated their operational reliability.²⁶ Nevertheless, the scope of the missions for Saturn V required additional changes and improvements. These alterations were introduced and checked out during the Saturn IB series, which not only carried the same basic instrument unit as the Saturn V but also involved manned launches and carried the similar S-IVB upper stage.

THE BRAIN AND ITS PARTS

Categorized as the "brain" and "nerve center" by the MSFC Astrionics Laboratory, the IU, with its modular construction, facilitated the changing of components and computer programs, without major modifications, for different missions. The basic functions of the IU included guidance and control during all phases of flight; command and sequence of vehicle functions, including engine cutoff and separation of the stages; insertion into orbit; and relay of data on vehicle position, vehicle functions, and other information to ground stations. In the case of the Saturn V, the IU also functioned in (1) the transfer of the S-IVB, the IU, and the command and service modules into the lunar transfer trajectory; (2) the stabilization during transposition and docking; and (3) the

STAGES TO SATURN

maneuvers to clear the S-IVB and IU from the flight path of the CSM on its route to the moon.²⁷ The IU itself was viewed as five major systems: structural, guidance and control, electrical, instrumentation, and environmental control.

The cylindrical IU structure did more than carry meters of cables, black boxes, and other miscellaneous paraphernalia; it was a load-bearing structure as well, with three major rocket stages stacked beneath it and thousands of kilograms of spacecraft, lunar landing module (and three astronauts) to support above it. The process of assembly of the IU began with three curved (120°) structural segments made of thin aluminum sheets bonded over an aluminum honeycomb core (approximately equal to the thickness of a bar of soap). In joining the three segments together, workers used highly accurate theodolites, much like a surveyor's transit, to align the three segments in a precise circle. Technicians joined the segments with precision-machined splice plates and affixed aluminum alloy channel rings for surface mating of both the S-IVB below and the payload above.²⁸

The key items for guidance and control included the ST-124 stabilized platform, the launch vehicle digital computer, and the launch vehicle data adapter. Produced by the Navigation and Control Division of the Bendix Corporation, the ST-124 consisted of a three-degrees-of-freedom inertial platform. With a diameter of 53 centimeters and a weight of 52 kilograms, the platform's structural members and most of its components were fabricated of beryllium, an extremely lightweight space-age metal. Although difficult to work with, beryllium offered significant weight savings and provided good stability over a wide temperature range. To reduce errors in sensing attitude and velocity, designers cut friction to a minimum in the platform gyros and accelerometers by floating the bearings on a thin film of dry nitrogen; pressure, temperature, and rate of flow were controlled from a reservoir in the IU. The carefully controlled alignment of the ST-124 platform did not take place until the final events of the launch countdown. The procedure called for a precisely sited theodolite not far from the launch pad to aim a beam of light through a small opening in the IU high above the ground. The beam passed through a small window in the guidance platform where a pair of platform prisms reflected the beam back to the theodolite. Coated to work with two different wavelengths, the prisms aided in aligning the platform to its launch azimuth; when proper alignment was achieved, the acquisition light signal notified the mission control center.²⁹

All the carefully engineered complexities of the Saturn guidance and control system were not fully employed during the first-stage burn. Although the ST-124 was released from its Earth-fixed reference to a space-fixed reference five seconds before liftoff and was supplying velocity and attitude data to the guidance computer during the first-stage burn, the vehicle did not require an active guidance system during the

boost phase. In ascent through the atmosphere, both the Saturn IB and Saturn V were subject to possible sudden stresses from gusts, wind shear, and jet streams. If the guidance computer, acting on signals from the stabilized platform, attempted to generate compensation maneuvers during such turbulence, the added stress forces from the powerful engines as they went through extensive gimbaling motions might cause the rocket to break up. So, during the first-stage burn, the rocket flew according to a predetermined program stored in its guidance computer. If the vehicle was forced off its predetermined path, the ST-124 sensed this displacement and fed the data into the computer for later retrieval. During the second- and third-stage burns, the stored data were run through the computer and into the active guidance and control system to put the rocket back on course.³⁰

Information on yaw, pitch, roll, and acceleration provided by the ST-124, as well as inputs from other electrical systems, were collectively assimilated and processed by the digital computer and the data adapter to give the rocket an optimum performance. There was a division of labor involved. The computer took information and provided commands such as orbital checkout of the vehicle. The adapter performed as an input-output unit in conjunction with the digital computer, interfacing with nearly all units of the astrionics system. Its digital section "buffered" the digital quantities, and an analog section converted analog to digital form and back again. The IU equipment for Saturn V was only slightly heavier and larger than that for the Saturn I, but its computer-data adapter combination was three times faster, possessed four times the storage capacity, and was far more reliable. Although there were seven times the number of electronic components in the Saturn V versions, their total power consumption was 100 watts less than in the Saturn I. Furthermore, the 460 000-bit storage design could be easily doubled by plugging in additional memory modules. The following table offers a quick comparison:³¹

Equipment Comparison
(Saturn I and V Computer/Data Adapter Subsystems)

<i>Item</i>	<i>Saturn I</i>	<i>Saturn V</i>
No. components	12 000	80 000
Weight (kg)	95	114
Volume (m ³)	1.1	1.6
Total power (watts)	540	438
Operations (sec)	3 200	9 600
Storage capacity (bits)	100 000	460 000
Reliability (hrs)	750	45 000

These statistical improvements do more than illustrate the significant changes in the IU for the Saturn IB/V, as compared with the Saturn

STAGES TO SATURN

I. They also reveal that, although original guidelines called for as little new equipment as possible, the nature of manned missions and the quest for reliability called for advanced design techniques. To meet the stringent reliability and operational requirements and also remain within the rigid size and weight limitations, four new design concepts were incorporated into the computer: a duplex memory system, unit logic devices, triple modular redundancy, and a liquid-cooled magnesium-lithium chassis.³²

The duplex memory system incorporated two separate sets of memory systems that operated in harmony during critical phases of the mission. This not only reduced the chances of system failure but operated so that one memory system could correct the other if intermittent failure should occur. The system consisted of six modules operating as pairs of duplex memories, each with 4096 computer words of 28 bits and designed to accept two additional modules for special mission requirements. The unit logic devices featured microminiature circuitry, resulting in a smaller, lighter system, having seven times more components than earlier computers while operating at three times the speed. Typically, each unit logic device was produced as a "wafer," 7.6 millimeters square and 0.71 millimeters thick. A total of 8918 such wafers were mounted on dozens of "pages," about 7.6 centimeters square, in the computer.

Further, the IU featured the first computer application where all critical circuits in both the computer and data adapter were triplicated—triple modular redundancy—giving near-ultimate operative reliability. Designers selected seven functional sections where catastrophic failure might occur but, for reasons of reliability, could not be permitted to occur. Each selected section was then placed in three identical but independent logic channels. Problems were presented to each module simultaneously, and the results of each, independently derived, went to a majority-rule voter circuit. Any dissenting "vote" was discarded as an error, and the only signal passed along by the voter circuit consisted of the identical signals from two of the modules. Voting disagreements did not appreciably slow the system: a worst-case voting delay would tie up the computer for only 100 nanoseconds (billions of a second). Moreover, the computer unit, occupying 0.6 cubic meter and weighing 35 kilograms, could subtract and add (in 82 microseconds) while simultaneously dividing and multiplying (in 328 microseconds).³³

The unusually light weight of the computer was achieved by the use of a magnesium-lithium alloy chassis, the first application of this alloy in structural fabrication for an electronics application. Weight being extremely costly in the upper stages of a booster, MSFC used the magnesium-lithium alloy construction, along with an integral cooling system, to save 29 kilograms. In selecting a suitable material, designers turned down the

FROM CHECKOUT TO LAUNCH

even lighter beryllium because of toxicity and technical difficulties in machining and boring. Magnesium-lithium was still quite light (25 percent less than conventional magnesium and 50 percent less than aluminum) and possessed a very high weight-to-strength ratio, good thermal qualities for operation in space, and minimal transfer of mechanical vibration.

In addition to sharing with the computer some similarities in the fabrication and production of the chassis, the data adapter incorporated concepts similar to those of the computer's unit logic devices and triple modular redundancy. The basic function of the data adapter was that of a "gateway" to the computer for all elements of the Saturn guidance system. It received inputs from the ground control computer, radio command channel, telemetry, multifarious communications from within the vehicle, the inertial guidance platform, and the flight control computer. For example, analog inputs from various sensors were taken by the data adapter and digitized for the computer. Computer outputs were relayed back to the data adapter for conversion to analog signals as required. If the signals involved control commands, they went through the analog flight control computer and were combined with additional signals from the rate gyros. The resulting output included commands to activate the engine gimbal systems, thereby changing the direction of their thrust and the attitude of the launch vehicle.³⁴

While some IU equipment maintained the rocket in flight, other systems were involved in communications, tracking the booster in trajectory and orbit, and transmitting reams of data back to the ground. Several tracking and command systems were employed: an Azusa system measured slant range and vehicle direction in relation to ground stations; a C-band radar transponder aided radar ground stations in measuring azimuth, elevation, and range; and a command and communications system permitted updating of the computer, performance of tests, addition or deletion of certain messages, and recall of certain portions of the computer memory bank. During launch and orbital phases, transducers throughout the vehicle reported information on vibrations, pressures, temperatures, and various operations; the measuring and telemetry system transmitted these data to ground stations. This not only furnished real-time data on vehicle performance during the mission but provided a means of checkout for succeeding events, verified commands to the vehicle, and created a bank of data for later analysis of the vehicle's overall performance.³⁵

The power to run this complex electronic equipment emanated from four 28-volt DC batteries, which consisted of special distributors and regulators for both low-voltage components and higher currents for the ST-124 inertial platform. The electrical system also included the emergency detection network to analyze vehicle malfunctions. Depending

STAGES TO SATURN

on the seriousness of the problem, the emergency detection network either responded with an automatic abort sequence or gave the astronaut crew and NASA flight controllers time to assess the situation.

Operation of the IU equipment generated considerable amounts of heat which had to be transferred away from the components and dissipated into space. This was the function of the environmental control system. It consisted of cold plates (as mounting surfaces for most of the electronic gear), and integral coolant passages for thermal control of (1) the computer, (2) the data adapter, (3) the flight control computer, and (4) the ST-124 platform. Heat was dissipated to a coolant mixture, similar to the antifreeze used in a car (60 percent methanol, 40 percent water), that was pumped through the 16 cold plates and the integral coolant passages. An additional 16 cold plates, located in the upper skirt section of the S-IVB, were also connected to the IU's coolant pumping system. Warmed coolant was pumped through a sublimator to reduce its temperature before it was routed back through the coolant passages and cold plates. A comparatively simple device, the sublimator consisted of a water supply to a porous plate with ice frozen in the pores, because the pores were exposed to the frigid environment of space. In the course of passage through the sublimator, heat from the coolant was transferred to the plate, the ice was converted to water vapor, and the water vapor was dissipated into space.³⁶

QUALITY CONTROL AND TESTING

To ensure trouble-free operation of the equipment in the IU, IBM established tightly controlled preparation and installation conditions during assembly of the IU. Tubing, valves, fittings, components, and subassemblies moved in a steady stream through various "clean-room" environments for checks and cleansing to establish minimums of contamination. MSFC specifications for the clean rooms varied, with increasing stringency ranging from class I to class IV rooms; this successively reflected greater requirements for clothing worn by personnel, temperature, humidity, and particle counts. For most clean-room operations, specifications allowed no particles greater than 175 microns in the air, although examination and qualification of some critical items established a limit of 20 microns—about the diameter of a human hair—and a count of no more than 6 per cubic meter. Cleaning for super-critical items included laminar flow work benches, de-ionized water, various combination of solvents, and ultrasonic systems. Once parts and assemblies were cleaned and ready for installation, there was the problem of transferring them from the clean-room environment to the "dirtier" area of IU assembly. Since the IU was too large to bring into the clean rooms, IBM

FROM CHECKOUT TO LAUNCH

decided to take the clean-room environment to the IU instead. The company used a trio of mobile clean rooms on casters, which had been hung with heavy vinyl curtain walls and equipped with air filters and blowers to maintain class IV working conditions.³⁷

Installation of equipment within the IU was accompanied by a series of checkout operations. Beginning with delivery of individual components, IBM personnel checked them against equipment specification drawings and subjected them to acceptance tests, followed by functional checks as items were mounted in the IU. As the various systems of the IU began to shape up, components and systems were checked until the IU was complete. Afterward, up to eight weeks of exhaustive simulation tests were conducted; these simulations included preflight ground checkouts and others for liftoff, trajectory, and orbit. When the test and simulation phase was complete, the IU was ready for shipment. Critical components, such as the ST-124, the computer, and the data adapter were taken out and packaged separately, then flown along with the IU to the Cape. At the Cape, these components were reassembled and rechecked before the IU was stacked into the rest of the vehicle and prepared for complete preflight checkout.³⁸

Despite the great emphasis on clean room facilities and spotless surroundings, IBM on one occasion finished production of an IU on the deck of a barge while floating down the Tennessee and Mississippi rivers. During 1965, work on the IU fell behind as a result of changes in instrumentation. The schedule for "stacking" the first Saturn IB (AS-201) for launch early in 1966 was apparently going to slip badly unless work on the IU could be accelerated. Marshall executives pressured their own IU project managers by demanding to know what they were going to do to make the launch date. Luther Powell and Sidney Sweat, from the IU project office at MSFC, brainstormed the situation and proposed a way to make up time. At that point, there was no aircraft large enough to deliver the IU by air. Instead, the IU was scheduled to be carried to the Cape via a barge down the Tennessee and Mississippi rivers, one of the most time-consuming elements in the IU delivery schedule.

Powell and Sweat proposed finishing the IU while enroute aboard the barge and submitted their idea to their IBM counterparts, who agreed with the unlikely proposal. Because the enclosed barge was equipped with internal environmental controls anyhow, it was no great problem to set up a workable clean-room atmosphere by rigging a series of heavy plastic shrouds for additional environmental control inside the barge canopy. Marshall and IBM specialists agreed on specific jobs to be done on the barge so that no critical areas or hardware would be subject to environmental degradation during the trip. With detailed work schedules set up, arrangements were made for delivery of key parts and supplies at designated ports along the river. In case of unanticipated

STAGES TO SATURN

needs, constant radio contact with MSFC permitted instantaneous dispatch of a light plane with emergency deliveries to any nearby airport; there, a government truck could pick them up and deliver them.

The unusual voyage worked. The IU was complete by the time it reached New Orleans. The most serious problems proved to be the physical condition of the traveling IU working team. Despite 16–18 hour workdays, the meals concocted by the barge's chef produced a chubbier group of electronics specialists by the end of the trip.³⁹

Barge trips being the exception, an intensive effort in quality control extended to the fabricating and manufacturing process and encompassed the subcontractors as well. In one instance, IBM began having leakage problems with the manifolds carrying the coolant of the environmental control system. On IU-204, engineers finally decided to restudy the whole process, since IU-204 was to be on a manned launch of the Saturn IB. Manifolds on other IUs in production were also removed, because these too were to be used on man-rated vehicles. The subcontractor, the Solar Division of International Harvester, had originally dealt with the frustrating problems of welding the aluminum alloy. During a thorough review of the procedure, Solar found that only minor variances in the use of the welding fixtures created the difficulties and thereafter imposed even stricter procedures for this crucial operation.⁴⁰ In spite of the constant theme of using proven hardware and systems, the different requirements of the Saturn program called forth some new equipment and attendant "teething" problems. Not infrequently, IBM sent delegations to vendors and subcontractors to help work out problems in quality control, welding, and soldering.⁴¹ In coping with these situations, IBM also called on MSFC technicians for assistance. A particularly dramatic instance occurred during the summer of 1967, when MSFC discovered cracks in the solder joints of the flight computer for IU-502, and IBM simultaneously discovered the same problem on IU-503. The discovery was unsettling for two reasons. In the first place, the units had already been man-rated and qualified for flight; the soldering problem should not have occurred. Second, the same kind of unit was already placed in vehicle AS-501, which was at Cape Kennedy being readied for the first launch of a Saturn V later in the year. Calling from Huntsville to NASA's Apollo Program Office, MSFC's Chief of Industrial Operations, Edmund O'Connor, warned Phillips in Washington: "Right now there is no impact, but this is potentially serious." It was decided to continue the checkout of AS-501 at the Cape, while sending a spare computer to the manufacturer, Electronics Communications Incorporated, for teardown, inspection, and rework of many of the solder joints. In this operation, technicians used a technique worked out by MSFC personnel in collaboration with their counterparts at the vendor's plant.⁴²

FROM CHECKOUT TO LAUNCH

STAGE SEPARATION AND ORDNANCE

For a Saturn V launch, the vehicle really began "thinking on its own" five seconds before liftoff when the IU was activated. The vehicle's control system first executed a series of time-programmed attitude maneuvers. After rising vertically for about 12 seconds, the IU's computer used stored roll and pitch commands to activate the gimbaled engines, thereby rolling the huge rocket to a proper flight azimuth and, at the same time, pitching it to the prescribed angle of attack for the first-stage boost. When the IU received a signal that the propellant level in the S-IC fuel tank had reached a specified point, it initiated commands for first-stage engine cutoff, followed by stage separation. Soon after the start of second-stage (S-II) ignition, the vehicle was controlled by a concept called "path adaptive guidance," which put the rocket on a trajectory that would use the propellants efficiently. About once every two seconds, the computer checked the vehicle's current position and flight conditions, comparing it with the optimum situation desired at the end of powered flight (altitude, velocity, residual propellants, etc.). As required, the IU generated correction signals from the computer through the data adapter to the analog flight control computer, which then issued appropriate gimbal commands to the engines. Engine cutoff and stage separation of the S-II from the S-IVB occurred when the IU sensed predetermined propellant levels. Because the vehicle had reached its approximate orbital altitude by this time, the S-IVB ignition and burn were fairly short—just enough time to ensure altitude and speed for a secure parking orbit.⁴³

If it became necessary to abort the mission, each Saturn carried a propellant dispersion system (PDS). This euphemism referred to a destruct mechanism to terminate the flight of any stage of the vehicle after the astronaut crew had separated from the rocket. The PDS system complied with regulations established by the officials of the Air Force Eastern Test Range and was under the control of the range safety officer, who could end the flight if the vehicle wandered beyond the prescribed limits of the flight path or otherwise became a safety hazard. A radio frequency unit received, decoded, and controlled the PDS commands, and an ordnance train demolished the stage or stages by rupturing the propellant tanks. The ordnance train included initiator assemblies and flexible linear-shaped charges situated in strategic locations to rip open the tanks after engine cutoff, spilling the propellants in a pattern to minimize their mixing during the process.⁴⁴

The Saturn rockets had other special ordnance requirements for stage separation and the use of retrorockets to ensure that the forward inertia of the lower stage after separation did not carry it into the stage

STAGES TO SATURN

ahead. The IU contained the program for arming and firing the ordnance systems both for stage separation and for triggering the retrorockets. The timing of the stage separation sequence was keyed to the rated thrust of each stage, which began to fall off as the propellants reached depletion. The stages were separated when an explosive device around the circumference of the vehicle severed a tension strap, thereby allowing the appropriate stage separation sequence to take place. As the retrorockets quickly pushed the spent stage backward, the next live stage continued in a short coasting trajectory to make sure adequate distance separated it from its predecessor and to resettle the propellants before engine ignition.⁴⁵ To decelerate spent stages and settle the propellants in each of the succeeding live stages, MSFC designers used a variety of rocket systems, including small solid-propellant motors and small liquid-propellant engines. The various models of the Saturn launch vehicle family actually carried more solid-propellant systems than liquid-propellant rocket engines: the Saturn I mounted 32 solid-propellant motors of various types; the Saturn IB mounted 31; and the Saturn V carried 22.⁴⁶

The Earth-orbital sequence of the S-IVB permitted the IU to compute reignition times continuously and take updated data from ground stations. With only one main engine for direct thrust control, the IU managed S-IVB roll, pitch, and yaw through its liquid propellant auxiliary propulsion system (APS). After final checks, the IU controlled the vehicle's entry into the translunar trajectory. A pair of jettisonable solid retrorockets and the APS together provided ullage control, followed by main-stage firing of the J-2 and engine cutoff when the IU reported that acceptable injection conditions had been achieved. Finally, when the spacecraft and lunar module disengaged from the S-IVB and IU, the IU and the third stage's APS units provided attitude stabilization for the transposition and docking maneuver. About 6.5 hours from liftoff, the tasks of the IU were finished.⁴⁷

SUMMARY: CHECKOUT, GUIDANCE, AND CONTROL

Development of checkout systems and the instrument unit reflected the same patterns as stage development. Despite attempts to rely on existing systems and equipment, the size and sophistication of the Saturn program required new development. New computer languages such as ATOLL were introduced to solve problems arising from the peculiarities of design, test, and several different contractors, each of whom had been using different computer languages. Automation of checkout and of static-firing tests of Saturn stages was a notable accomplishment, even if some test engineers were reluctant to surrender control to new, electronic masters.

FROM CHECKOUT TO LAUNCH

The instrument unit, using many theories and design features that originated in the wartime V-2 program in Germany, is an interesting example of technology transfer. Of course, the Saturn program itself generated several advanced ideas. The need to reduce weight stimulated new research into the use of beryllium and lithium-magnesium alloys; reliability and operational requirements stimulated new research in microminiature circuitry such as the triple modular redundancy.

Obviously, each contractor had a responsibility for managing its own respective engine, stage, or instrument unit. Overall management and coordination of these various elements was NASA's responsibility, a job carried out by the Marshall Space Flight Center, which also supervised the delivery of the Saturn's various parts to test sites and to Cape Kennedy for launch.

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V

Coordination: Men and Machines

Management of the multifarious elements of the Saturn program entailed new tasks and concepts beyond the scope of any previous rocket program. As explained in chapter 9, MSFC's management was a dynamic process. Although rooted in the experience of the von Braun team, dating back to the 1930s, Saturn management responded to internal stimuli as well as external influences, including the prime contractors, NASA Headquarters, and other sources.

Almost last, but far from least, the challenge of transporting rocket stages of exceptional size to test and launch sites posed equally unique complications. Logistics became a special management task. Chapter 10 explores some of the ramifications of moving the Saturn stages from points as far away as the Pacific coast to the launch pad at Cape Kennedy, with intermediate stops for static-firing tests and other checks.

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9

Managing Saturn

In 1962, pausing to look back over a career in which he played a key role as a leader in rocket research, Wernher von Braun noted two significant factors of success. First, the group of German rocket experts, known as the von Braun team at NASA's Marshall Space Flight Center (MSFC), had been a "fluid, living organization," shaped by and responding to external forces. Second, in three decades of consistent activity at the forefront of rocket development, an activity conducted with a "singleness of purpose, we have had only one long-range objective: the continuous evolution of space flight," von Braun emphasized. "Ever since the days of the young Raketenflugplatz Reinickendorf in the outskirts of Berlin in 1930, we have been obsessed by a passionate desire to make this dream come true." Despite the changes over the years in personnel, in geography, in nationality, and in bureaucracies, von Braun continued, "many of our methods have remained unchanged."¹ Many of these methods would persist during the Apollo-Saturn program and carry over into other phases of management at Marshall Space Flight Center.

No major Saturn component, whether engine, stage, or instrument unit, evolved without numerous—and continuous—problems. The persistence of various snarls is easily perceived by dipping at random in von Braun's "Weekly Notes" or "Daily Journal" from 1961 through 1970. Predicaments occurred everywhere and every day. Although complications in the Saturn program lingered, it is apparent that the most annoying problems tapered off during 1966. With increasing frequency, entries in the "Weekly Notes" and "Daily Journal" reported tests "successfully accomplished," results "well below red line," and hardware with "component qualification complete."²

STAGES TO SATURN

The rising note of technological optimism in the Saturn program stemmed from the elaborate research, development, and test programs, followed by carefully controlled fabrication and manufacturing guidelines instituted by both NASA and contractors and managed by MSFC.

THE DIRECTOR OF MSFC

As Director of the new Marshall Space Flight Center in 1960, von Braun faced some immediate managerial challenges. The core of the staff had come from ABMA's Development Operations Division, which he had directed for the Army. But that division had been a research and development group depending on other ABMA offices for ancillary support and administrative services. After the transfer to NASA, the MSFC director had to develop an administrative as well as technical staff, in addition to providing procurement contracting, facilities engineering, and other support services. The von Braun team not only found itself in a civilian organization for the first time, but also the style of operations had changed. There were new responsibilities for numerous projects, as opposed to the ABMA experience of dealing with only one prime project at a time.³

In spite of the increased responsibilities under the MSFC organization, management retained a distinctive in-house capability—what von Braun liked to call the “dirty hands” philosophy. This attitude, resulting from years of active work as a research and development group in Germany and from the Army arsenal concept of the ABMA days,



Wernher von Braun (right), Director of Marshall Space Flight Center, listens attentively to a briefing on metal forming techniques by Mathias Siebel, of MSFC's Manufacturing Engineering Laboratory.

provided a number of exceptionally strong laboratories and shops at the Huntsville facility. Managers and engineers were never very far from each other, and the relationship (and its elaboration) persisted as a key element in the success of MSFC's management of the Saturn program.

Technical competence was more than a catchword at Marshall; it was a way of life. As Director, von Braun somehow succeeded in keeping up with the paper work and budget reviews involving NASA and his own center, and at the same time, he kept an eye on minute technical details of the Saturn program. In 1967, for example, when von Braun received a weekly note on propulsion systems, he noticed that inlet pressures for the S-II center engine had been simulated at 1900 grams per square centimeter (27.0 pounds per square inch adiabatic) during J-2 engine tests. In the margin, von Braun jotted a note for one of the project engineers: "If I remember correctly, that would enable us to lower the LH₂ tank pressure in the SII by 2 psi. . .right? What are the SII people now *actually* doing?"⁴

Throughout his tenure as Marshall's director, von Braun required such "Weekly Notes" from the laboratory chiefs and program managers, as well as from other personnel on an ad hoc basis when a problem was brewing. He was adamant about the length of these Weekly Notes, warning "notes exceeding one page will be returned for condensation." As the notes crossed von Braun's desk, he emphasized various points with check marks and underlined phrases and scribbled assorted messages in the margins: a compliment; a request for information; dismay; encouragement; and miscellaneous instructions. Reproduced copies went back to the originator with marginalia intact. Although curt and to the point, the replies were invariably personal, and occasionally tinged with humor. Informed of a possible strike by the janitorial contractor, von Braun responded, "Get me a broom! I'll sweep my own office."⁵

At the innumerable meetings attended by von Braun as chairman or participant, he displayed a remarkable ability to distill complex technical issues into terms that other participants could understand. Matt Urlaub, S-IC Program Manager, recalled technical presentations "that lost me in the first five (minutes)." After listening, von Braun would sum up the presentation in language clear to everyone. Yet von Braun consciously avoided dominating such sessions and attempted to bring out all opinions. These techniques contributed to genuine "team spirit." Konrad Dannenberg, a key manager and associate of von Braun since the days at Peenemuende, stressed the point: "You have to get all the people involved. Von Braun has a real good flair for that," he said. "Everyone, when he has a meeting with him, feels like the second most important man . . . and boy that really gives you a team spirit. Everyone is willing to do his best." Von Braun employed this trait effectively during tours of Marshall laboratories and contractor plants. He met with senior executives, but he also took a personal interest in what was happening on the

STAGES TO SATURN

shop floor—the problems, the progress, and the tools. Von Braun talked just as easily with the “top brass” as with the “tin-benders.” These tours had great significance in improving morale, and von Braun made periodic tours intentionally. The tours were helpful to him too, in sensing the pace of the program as well as the nature of difficulties as they developed.⁶

This concern for technical aspects was a hallmark of Marshall planning, and von Braun personified it. In the earliest phase of Saturn design at ABMA, Frank Williams, an ABMA veteran, remembered von Braun’s consistently close involvement. “It was just a ball working,” Williams said, “having him [von Braun] come down and literally pore over the drawing boards with you, and look at the performance and check the engineering work.” Williams went on to say that when the Saturn V design was being established, von Braun was in the forefront, immersing himself in the whole vehicle: structures, systems, and missions.⁷ This is not to say that only the Director and a small handful of top aides did the conceptual work and forced it through. One of the reasons for the Saturn success, Dannenberg emphasized, was “because a lot of real good down-to-earth planning was done at the beginning.” Von Braun solicited advice and suggestions from workers in the shops, taking into account the realities of fabrication and manufacture as the design evolved. In this way, Dannenberg explained, von Braun avoided the pitfalls of having top-level managers making critical decisions among themselves and making assumptions about production that might not approach reality.⁸

These tenets, among others, guided von Braun and his staff at Huntsville. Many other issues of organization, administration, and accountability had to be solved. The Saturn program was large, expensive, and involved complex contracts. According to one source, von Braun remarked that when he came into NASA, he knew how to go to the moon, but he did not know what a billion dollars was.⁹ Like other NASA administrators, von Braun soon learned to handle billion-dollar programs with aplomb.

EARLY SATURN MANAGEMENT

Eberhard Rees, who succeeded von Braun as MSFC’s Director in 1970, said that when the Apollo-Saturn program was inaugurated in the early 1960s, the adolescent NASA organization had no comprehensive management apparatus; the management system developed “after some painful experiences” during the early development period. The management organization for the overall NASA program, as well as for MSFC, was not set up in a flash of insight, to remain unchanged for the duration of the program. Rather, as the program gained momentum and the configuration of the launch vehicles began to evolve, management

MANAGING SATURN

organization and tools also evolved, changing the programs over the years. As Rees observed, one of the axioms in the evolution of a large development project was that no static system of management would suffice.¹⁰

During January 1960, when affiliated with ABMA, von Braun and his staff began to set up a management plan that would meet the approval of NASA Headquarters. The laboratories would continue to report directly to von Braun, and a new organizational position for a project director of the Saturn vehicle system was proposed. Details of vehicle integration, planning for R&D, and mission payloads were worked out through a separate Saturn coordination board, chaired by von Braun. The arrangement was rather unwieldy, and was never completely implemented. However, the correspondence from Huntsville to Washington requesting approval reveals the strong influence of NASA Headquarters in early Saturn planning, including details of contractor selection. The early influence of the laboratories and their chiefs is also evident in the membership of the "working groups" that made up the Saturn coordination board.¹¹

The management organization for the early period of the Saturn program, when the Saturn I was the only launch vehicle being developed, relied on the Saturn Systems Office (SSO). At the heart of SSO were three project offices: Vehicle Project Manager; the S-I Stage Project Manager; and the S-IV and S-V Stages Project Manager (the S-V was a small third stage that was ultimately dropped from the Saturn I configuration). The vehicle project manager cooperated with the stage managers in overall vehicle configuration and systems integration. The Saturn I first stage was produced and manufactured in-house by MSFC at Huntsville, and the production of the upper stages as well as the engines and the instrument unit involved management of several other contractors. The SSO was a comparatively small office; in the spring of 1963 it employed only 154 people. Its operation was based primarily on the strength of other center administrative support offices and the work of the "line divisions." The line divisions were based on the nine technical divisions, or laboratories (each composed of several hundred people), carried over nearly intact from the ABMA days.

The laboratories themselves carried significant prestige within the center and benefited from very strong support from von Braun. In fact, most technical decisions were reached by consensus during the "board meetings" of von Braun and the laboratory chiefs in executive sessions. For the lower stages of the Saturn I vehicles, produced in-house, this arrangement proved workable; and it must be remembered that the laboratory chiefs had worked this way for years, first at Peenemuende and later at ABMA. Much of the work in SSO concerned funds and liaison with NASA Headquarters. This was conducted in a very informal manner, with SSO personnel frequently visiting Washington.¹²

STAGES TO SATURN

The growth of the Saturn program to include development of two new launch vehicles caused a reappraisal of the production and management organizations. The finalization of plans during 1962 for a two-stage Saturn IB (for Earth-orbital manned Apollo hardware tests) and the three-stage Saturn V (for the manned Apollo lunar landing missions) enlarged the scope of SSO and prompted the shift of MSFC into a more comprehensive management role. The change was underscored by von Braun in remarks to a management convention in 1962, when he observed that "our rocket team has become today more than ever a managerial group." The Saturn IB and Saturn V manufacturing programs were far beyond the in-house capability of MSFC and available government resources, so that large-scale contracts under MSFC management were required. The von Braun group had some experience in the practice of accomplishing tasks through contracts. Outside of Peenemuende, important research work involving the V-2 was done by German universities in aspects of propellants, trajectories, and propellant systems. German industry also contracted for research and development of guidance and control systems, as well as turbopump machinery. The von Braun team had developed managerial skills in working with American contractors who built the Redstone, Jupiter, and Pershing missiles. Because of the size of the Saturn program and the diversity of the major contractors and subcontractors from coast to coast, a different management organization was required. The task of developing and integrating two or three large, complex stages and an instrument unit into a single vehicle that would mate with the spacecraft and launch facility was compounded by the multidisciplinary problems of weight, size, and manrating. The complexity was further increased by budgetary constraints and tight schedules. In responding to these new demands on management, both MSFC and NASA Headquarters changed existing agency techniques, developed new ones, and remodified techniques in response to changing conditions.¹³

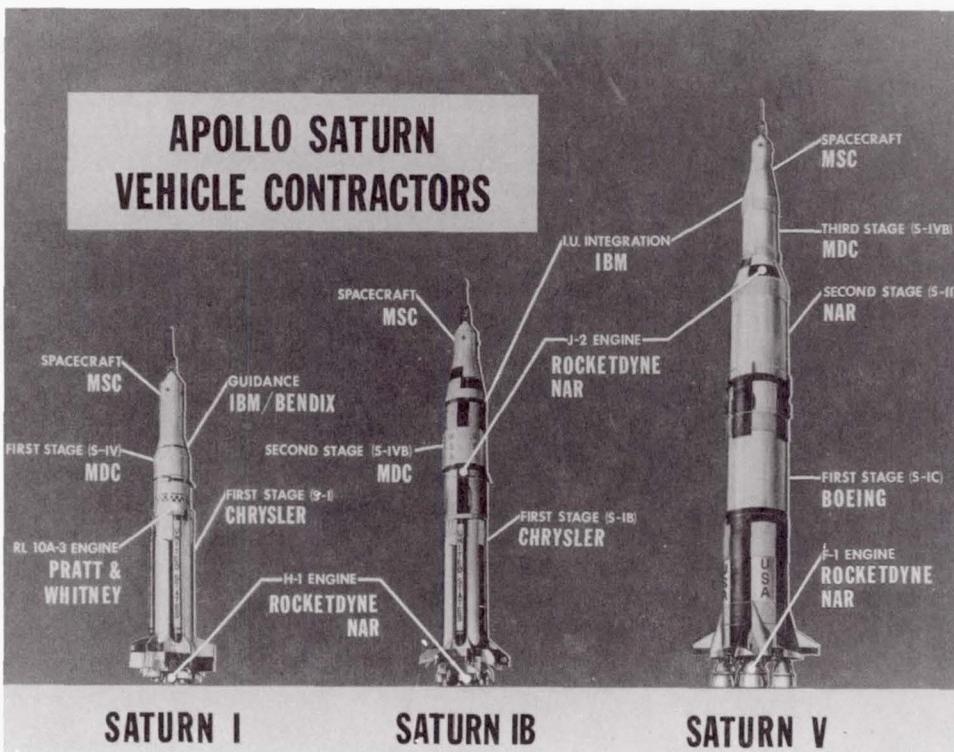
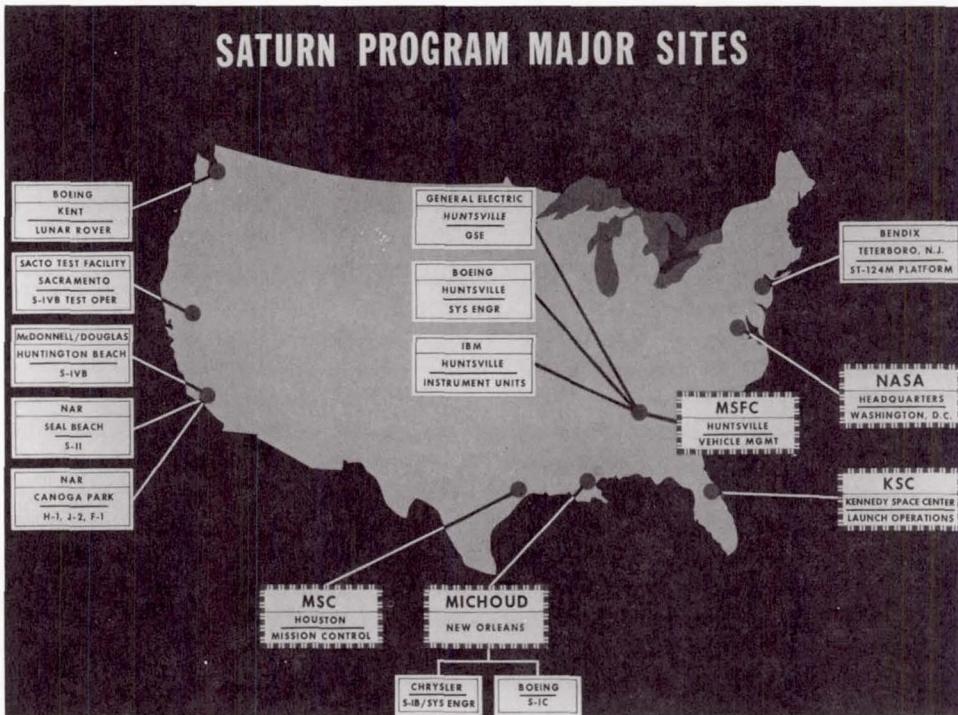
The reorganization of SSO in 1962 combined the similar Saturn I and IB vehicles under the management of a single office, established the Saturn V Launch Office, and set up the Saturn-Apollo Systems Integration Office. The reorganization further incorporated a new emphasis on these "project offices," that were empowered to draw directly from the expertise of the technical divisions. Internally, the technical divisions of MSFC did not change much more under the new NASA organization and continued to report directly to von Braun. As before, divisions were not designated specifically to projects, but were organized by professional disciplines—electronics, mechanical engineering, flight mechanics, and so on. Each division director had the responsibility to maintain a high level of expertise in his organization, keeping up with work in industry and other government agencies and carrying on theoretical research. Von Braun reminded everyone, "The technical people [must] keep their

hands dirty and actively work on in-house projects selected specifically for the purpose of updating their knowledge and increasing their competence." These practices were necessary to enable MSFC to cover all phases of development, production, and shop work. Von Braun emphasized that this policy was the best preparation for evaluating contractor standards and proposals. The goal was to achieve the best economics in overall work and to get the maximum results for taxpayer dollars.¹⁴

Von Braun noted in a memo on the reorganization, "It is important to spell out the responsibilities of the project offices in contrast to those of the technical divisions." The project offices managed efforts involving more than one discipline and reported directly to von Braun. Because of the technical complexity and scope implicit in project management, each office required technical support in depth. "It gets this support, not by creating it within its own organization, but by calling upon the technical divisions," von Braun wrote. He left no doubt about the vigorous role of project managers in the future operations of MSFC: "Since the direction of the various projects assigned to our Center constitutes our primary mission, I would like to make certain that Division Directors fully understand and fulfill their responsibilities in support of the management of those projects."

The 1962 MSFC reorganization reduced the premier position of the technical divisions, or laboratories, and marked a historic break in the evolution of the Peenemuende group. As Bill Sneed recalled, the change was "painful" for von Braun to make. In his three-page memorandum explaining the change and the reasons for it, von Braun urged personnel, especially his division heads, to accept gracefully their changed status. "In the past, such a paper was needless," he wrote, and went on to explain the requisite logic for the new management responsibility in the program and project offices. "By keeping these principles in mind, and maintaining the spirit of teamwork which has been our tradition, we can adjust to our new conditions and retain our past performance standards."¹⁵

As the momentum of the Apollo-Saturn program increased and the activities of NASA Headquarters proliferated in response to the manned lunar landing program and other programs, a major reorganization was planned to cope with all the expanding operations. The reorganization involved all the major centers taking part in the Apollo-Saturn program,¹⁶ and the change at Marshall Space Flight Center set the style for its operations for the next six years, the major period of Saturn V development. The change at MSFC strongly reflected past organizational arrangements, but also increased the authority of certain segments of the managerial structure. In addition, the change established successful new working arrangements between NASA Headquarters and MSFC, as well as within MSFC's new organizational framework.



MANAGING SATURN

THE SATURN PROGRAM OFFICE

Effective 1 September 1963, the center director's office (with appropriate staff and functional offices) directed two new operational elements: the Research and Development Operations (R&DO) and Industrial Operations (IO). Both of the new organizations possessed equal operational authority, and both reported directly to von Braun as Director of MSFC. Operations between the two organizations, however, were continuous, and certain elements on the Industrial Operations side had a direct continuous relationship with NASA Headquarters.¹⁷ The new director of R&DO, Herman Weidner, was a long-time member of the von Braun team from the Peenemuende era—a man with whom the other von Braun team veterans could work. The new IO director, on the other hand, came from industry, and reflected IO's contractual and managerial functions. The first IO director was Robert Young, formerly of Aerojet General. He played an interim role for about a year, and was succeeded by General Edmund O'Connor, on leave from the Air Force.¹⁸

Young's decision to accept the job had delighted von Braun. Young seemed to have the managerial talents and industrial know-how that management of the Saturn program demanded.¹⁹ For personal reasons, Young decided to go back to Aerojet, although some insiders at Huntsville thought that he found it somewhat difficult to adjust to Marshall's style of operations. Executives at Young's level still had to clear many decisions through NASA Headquarters, as well as through von Braun's office; managers coming into Marshall from private industry frequently found the additional bureaucratic layers to be irksome. Also these executives soon found that some subordinates at MSFC frequently disagreed with the boss, even in large meetings. To some executives, this bureaucratic democracy could be unsettling. In any case, the appearance of Edmund O'Connor reflected an interesting tendency to bring on board a number of Air Force officers with managerial credentials. Despite its Army heritage, MSFC seemed to favor Air Force personnel in several key positions. They not only had experience in the ways of government bureaucracy, but also had more experience in managing large, complex missile systems, compared to the Army's responsibilities for smaller, artillery-type rockets.²⁰ In the autumn of 1964, the Air Force transferred 42 field-grade officers to various mid-level management jobs throughout NASA. Experienced in technical program management, these officers were especially versed in configuration, program control, and quality assurance. Marshall Space Flight Center received a dozen Air Force officers, with the rest sent to Houston, Kennedy Space Center, and George Mueller's office at NASA Headquarters.²¹

Whether the new MSFC missile managers came from the Army, Air Force, civil service, or private industry, they still had to function within the administrative framework of the 1963 reorganization agreed to by

STAGES TO SATURN

Marshall and NASA Headquarters. At MSFC, the two major components that had to mesh were R&DO and IO.

In essence, the R&DO laboratories were direct descendants of the older technical divisions, and the Industrial Operations elements were modifications of the former Saturn Systems Office. At the heart of the Industrial Operations organization were the three program offices, established for the direct management of the industrial contractors who had responsibility for the Saturn launch vehicles: the Saturn I-IB Office, the Saturn V Office, and the Engines Office. The function of the new Engines Office was to shift responsibility for engine development and production from the laboratories to Industrial Operations, in keeping with the intent of the 1963 reorganization for better management control by means of program and project management.²²

Each program office was set up similar to the Industrial Operations organization, so that each program manager had a cluster of small, dual-purpose staff and functional offices in addition to the project offices for technical management. Some closely structural elements were combined. The Saturn V Program Office, for example, managed the S-IVB stage, used on both the Saturn IB and Saturn V. Similarly, because some engines were used in more than one stage or vehicle, direction of the engine program was more effectively guided from one responsible Engine Program Office.

Arthur Rudolph, head of the Saturn V Program Office, emphasized that the managers of the staff and functional offices were not simply staff but were equal to the project managers for each of the project offices under Rudolph's jurisdiction. The staff and functional offices had multiple roles because they supported not only the program manager but each of the project management offices, and they interacted with NASA Headquarters as well.²³ The staff and functional office managers were known informally in NASA circles as the "GEM Boxes" after George E. Mueller, who headed the Office of Manned Space Flight.

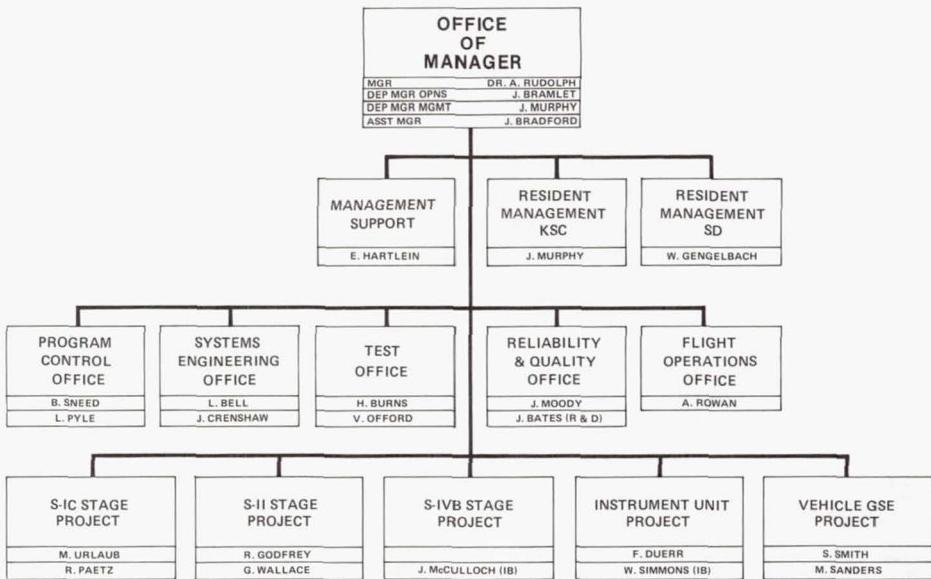
Formal guidance and direction from Headquarters to the centers came down through the Associate Administrator for Manned Space Flight, to the center director, and to the program manager, but daily informal management was accomplished through the GEM Boxes, who provided a "mirror image" between Headquarters and the centers.²⁴ The GEM Boxes in the centers, identical to those in Mueller's office in Washington, facilitated a daily, and free, flow of information in both directions. "Since like persons were talking at both ends," commented one long-time observer of the system, "confusion and misunderstanding with accompanying loss of time and funds were held to a minimum." The impetus for this aspect of the managerial apparatus primarily came from Mueller. During visits to MSFC, Mueller emphasized to von Braun that the laboratories (R&DO) were going to have to adopt more of a support

role in the new program management structure, and that better communications with Headquarters through IO were urgently required. Mueller felt that the centers in general were too independent in their relationships with Headquarters and that lack of regular communications was a serious shortcoming. "So I put together this concept of a program office structure, geographically dispersed, but tied with a set of functional staff elements that had intra-communications between program offices that were below center level and below the program office level so as to get some depth of communications," Mueller said.²⁵

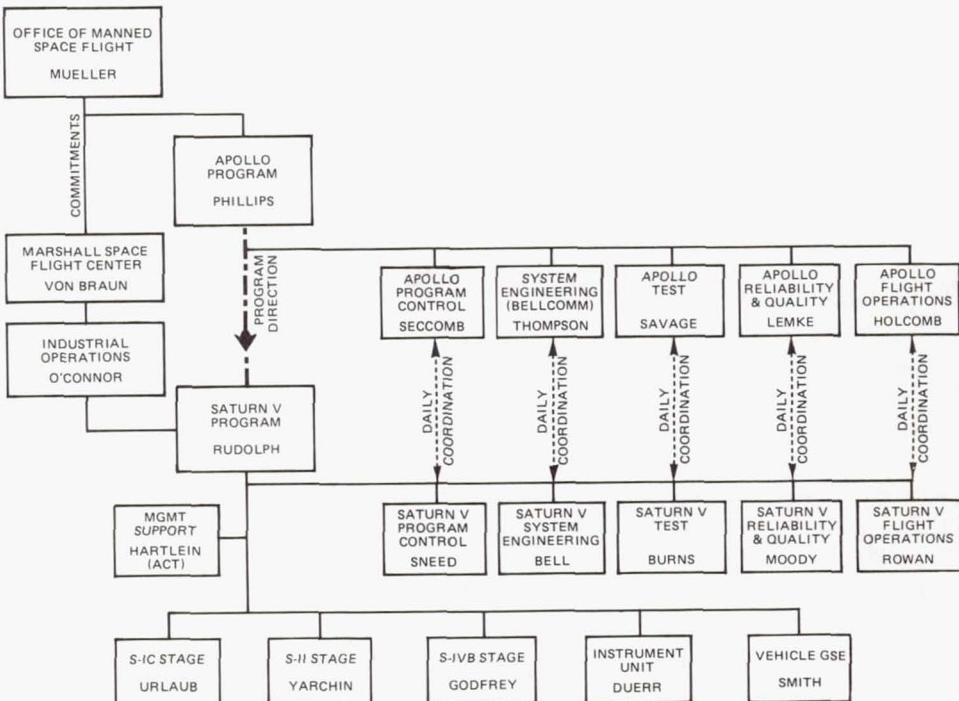
Following the 1963 reorganization, the new program office began to formulate a mode of operations. As head of the Saturn V Program Office, Arthur Rudolph called on considerable managerial expertise in project management of rocket vehicles dating back to the years at Peenemuende, and especially during the ABMA period when he served as project director for the Army's Redstone and Pershing programs. From 1961 through 1963, he had worked at NASA Headquarters, in the Systems Engineering Division of the Office of Manned Space Flight. He had watched the plans for the Saturn V evolve and was aware of such factors as schedules, funds, and performance requirements.²⁶ He also had specific ideas of how his program was going to run and placed considerable emphasis on what he called program element plans. Rudolph's staff often chafed under the requirements to write up these rather specific documents, which detailed what each office was going to do and how it was going to be accomplished. Most of the skeptics finally came around, however. The program element plans forced people to think about the goals and mechanics of their respective operations and how their operations interacted with the operations of other offices. Even if the authors seldom referred to the documents, they proceeded with greater success because they were forced to analyze the procedures from the start of the project. "I think the major problem is that in a big program like the Saturn V you have many people involved and usually people want to go off on tangents," Rudolph explained. "And the biggest problem is really to get them all to sing from the same sheet of music, to put it in the simple fashion. That's the biggest problem."²⁷ James T. Murphy, who acted as Rudolph's deputy manager of the management division, summarized the role of his chief: "In its simplest concept, a program manager, with a supporting staff, has been designated to coordinate the efforts of all Government and private industry groups in developing and producing the Saturn V launch vehicle."²⁸

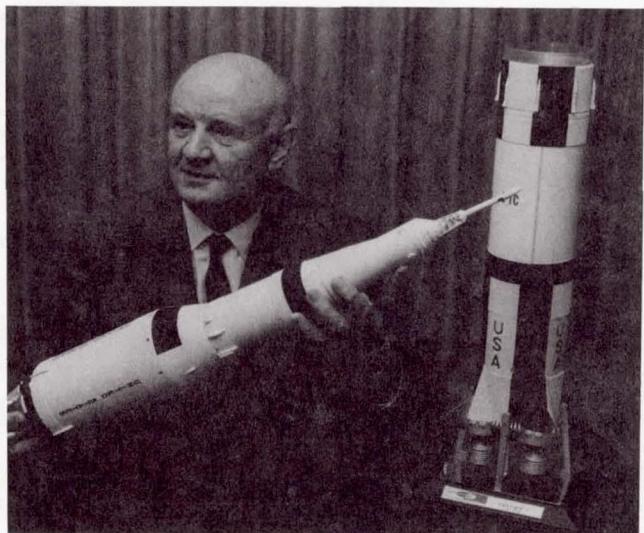
A major instrument in establishing a managerial approach was the Saturn V program control system plan, originated by Rudolph's office in 1965, and known as Directive No. 9. The objective was to establish a "baseline definition," against which progress could be plotted, problems highlighted, corrective actions taken, and management kept informed.

MSFC SATURN V PROGRAM



Above, organization of the Saturn V Program Office at Marshall Space Flight Center; below, diagram of George E. Mueller's GEM boxes, showing NASA Headquarters' "mirror image."





Arthur Rudolph, manager of MSFC's Saturn V Program Office.

Directive No. 9 instructed personnel in the Saturn V Program Office to implement the management approach in five major areas:

1. Baseline definition
2. Performance measurement and analysis
3. Problem resolution
4. Management reporting system
5. Program control center

The baseline definition was primarily geared to matters of cost, schedules, and performance, and was achieved through program elements such as logistics, finance, and testing. The program elements comprising the baseline definition were under the control of the staff/functional offices known as the GEM Boxes.²⁹

- Program Control Office: Primarily responsible for costs and budgets, progress reports, and logistics, including manpower and facility requirements, scheduling and contracts, and configuration management.
- Systems Engineering Office: Responsible for mission description, overall systems specifications, and systems description.
- Test Office: Charged with test planning, performance, coordination and standards, and for the establishment of checkout requirements and coordination.

STAGES TO SATURN

- Reliability and Quality Office: Responsible for establishing and maintaining reliability and quality standards, including contractual requirements, compilation of statistics, and failure reports.
- Flight Operations Office: Charged with assuring that all flight hardware was ready for manned flight operations, including the establishment of necessary requirements, plans, and coordination.

INTERFACES AND INTER-CENTER COORDINATION

The interfaces to be controlled throughout the Saturn program, such as those between stages, between the payload and the vehicle, and between the vehicle and the launch facilities, seemed limitless. With contractors and three major NASA centers in the Apollo-Saturn program, the interface problems covered physical, functional, and procedural areas, and these problems often became intertwined. The necessary documentation included both drawings and written directives to establish basic responsibilities as well as the limits of responsibilities for the parties involved. Once established, such documentation could not be altered unless all parties came to agreement on terms.

The interface aspects were established at the beginning of the Saturn V program with collaboration of appropriate inter-center coordination panels, working groups within MSFC, contractor advice, and a strong input from the R&DO laboratories at MSFC.³⁰ When a contractor originated an engineering change proposal against the current configuration, he knew in advance the impact on other equipment and organizations, since the interface documents were already drawn up. Contractors had the opportunity to coordinate possible changes ahead of time by notifying related personnel of the time of the change and its ramifications.

Difficulties often cropped up during the process of interfacing various stages of the launch vehicle, spacecraft, related equipment and systems, and the various centers. To maintain configuration control, a group of inter-center coordination panels was established to resolve the interface problems. Technical personnel were appointed from the centers and from other NASA agencies. The formal communications media between panel members involved the interface control documents. The documents were divided into two levels: level A documented technical interfaces between the centers and level B did the same for hardware supplied by the NASA contractors. If the change concerned a single stage and involved no other interfaces, then the proposal could go through a change board at the project level at MSFC. If the change affected the interface with hardware on a different stage, it had to go to the program level (level B). If the change affected the program of a different NASA center, it was necessary to go through the inter-center coordination panel

MANAGING SATURN

to reach a decision (level A). In situations where the panel could not reach a decision, an executive group, the Panel Review Board, supervised and adjudicated the issues as necessary. The Board was chaired by the Apollo Program Director at NASA Headquarters and channeled its decisions back through the appropriate centers and program offices.³¹

Within MSFC itself, there were a number of "working groups" that originated early in the Saturn program to cope with various development problems that had cropped up. These groups became the acknowledged elements to work on the various interface problems concerning Huntsville's work on the Saturn program. The working groups were originally created in 1960 by Oswald Lange, who at that time headed the Saturn Systems Office, "to make available the experience of MSFC and contractor representatives toward the solution of stage interface and system problems." The purpose of the groups was not to deemphasize the responsibilities of other MSFC organizations or those of the contractor, but to monitor special areas and make informed, incisive recommendations through appropriate channels. The number of such working groups varied from time to time, with each group chaired by a senior technical authority from one of the laboratories, and including representatives from the appropriate program offices. Group recommendations were channeled through the Program Office Configuration Control Boards.³²

To gauge the status of the program and to assess its progress, hundreds of MSFC personnel engaged in various levels of daily, weekly, and monthly staff meetings. Although informal contact between Saturn V Program Office personnel and contractor personnel occurred daily, in addition to recurring visits to contractor plants, the most important formal meeting was the Contractor Quarterly Project Review beginning in late 1964. In these meetings, contractor and MSFC managers reviewed not only the technical status of the project, but also the management status. In the meantime, the Saturn V program manager's office customarily held various staff meetings with each of the project managers in Huntsville, and also conducted a more elaborate monthly Saturn V Program Review with all of the project offices involved. These sessions, begun early in 1965, kept the program manager fully informed and provided an additional forum to cope with related problems. Rudolph did not like frequent staff meetings. Instead he liked to have fewer meetings in which the programs were discussed and analyzed in depth, leaving the management burden in the interim primarily on the shoulders of his project offices. This meant that the monthly sessions were very long indeed, and one of the standard jokes in Rudolph's office involved bleary-eyed project managers, in the early morning hours, dropping notes out of office windows: "Help me—I'm in a Rudolph meeting!"

These monthly sessions helped to generate information for the Management Council meetings for the Office of Manned Space Flight

STAGES TO SATURN

(OMSF), convened by the Associate Administrator at NASA Headquarters each month, or as required. For these meetings, the program managers and other designated personnel accompanied the MSFC director and participated in analyzing problems and progress, while at the same time receiving Headquarters information on policy changes and various program directives. The format was usually concerned with four main issues:³³

1. Where did the money go and can we manage within the allotted funds remaining?
2. What preplanned tasks have been accomplished and can we meet the projected schedule?
3. What are our major technical and programmatic problems and what previously unforeseen actions must be taken to overcome them?
4. What are our major motivational problems?

In addition, two other top-level meetings were customary in the Saturn program, one within NASA management and one that included the contractors. OMSF conducted an annual Apollo-Saturn program review attended by NASA Administrator Webb and selected staff. The center directors attended, and formal presentations were made by designated senior executives from the centers. These annual reviews gave the Administrator a comprehensive and critical analysis of contractor and program performance over the past year, with projections for the year ahead. As required, George Mueller occasionally convened what he called the Apollo Executive Group. This group involved the chief executives of the contractors in the Apollo-Saturn program. They met at various major contractor sites for briefings and visited each of the major NASA centers. Mueller said that without the Apollo Executive Group, "we would not have been able to succeed—it was one of the things that made it possible to succeed." All of the chief executives became aware of the problems and possibilities, and felt involved in the program. The meetings also gave NASA and the centers "top level interest and support."³⁴

At a different level, the Saturn program used a technical review system to ensure that development, design, fabrication, and test activities for each stage were properly evaluated. These reviews, such as critical design reviews and flight reviews, were attended by senior technical experts and top management.

RELATIONSHIPS WITH THE CONTRACTOR

Aside from the various communications, visits to the contractor facilities, and quarterly reviews with the contractors, the Saturn V Program Office had immediate representation at major contractor plants



NASA Office of Manned Space Flight Management Council: the principals, George E. Mueller (third from left), Associate Administrator for Manned Space Flight and chairman, with manned space flight center directors Wernher von Braun (MSFC), Robert R. Gilruth (MSC), and Kurt H. Debus (KSC).

in the form of the Resident Manager's Office (RMO), which consisted of the head of each office. At each location, the RMO operated as a "mirror image" of the respective project manager back in Huntsville. The RMO was directly responsible to the project manager, and communicated with him daily. Each RMO had a small staff of technical and contractual personnel from MSFC and, as the primary liaison between MSFC and the contractor, exercised a reasonable amount of authority.³⁵

Since the role of the RMO was to expedite decisions, a small cadre of specialists was "to assure that project management interests were advanced and that decisions were made and implemented within the designated scope of authority of the resident group." Guidelines supplied to the RMO allowed him to make certain on-the-spot decisions with the backing of his staff. These decisions included making commitments in behalf of other offices and/or functions of the center. "This resident element proved to be a most important link between government and contractor activities in the management of large programs." In MSFC's opinion, the process of management was accelerated as a result of this on-site authority, and provided a "dynamic interface" between MSFC and the contractor.³⁶

Eberhard Rees admitted that the surveillance of contractor operations, as well as their management, was "somewhat sensitive from the point of view of the contractor." In many instances, contractors felt that

STAGES TO SATURN

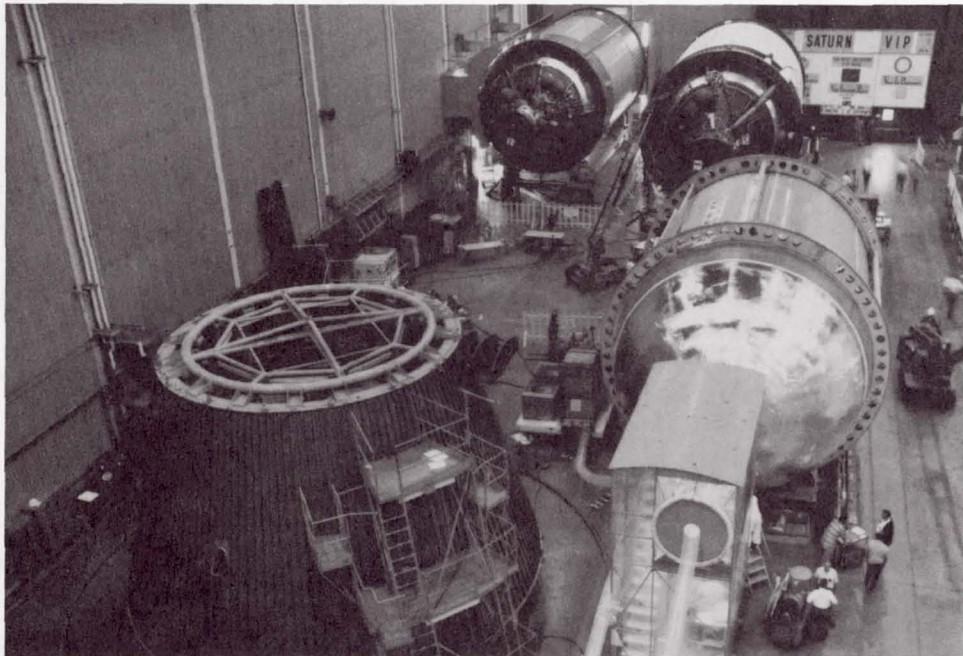
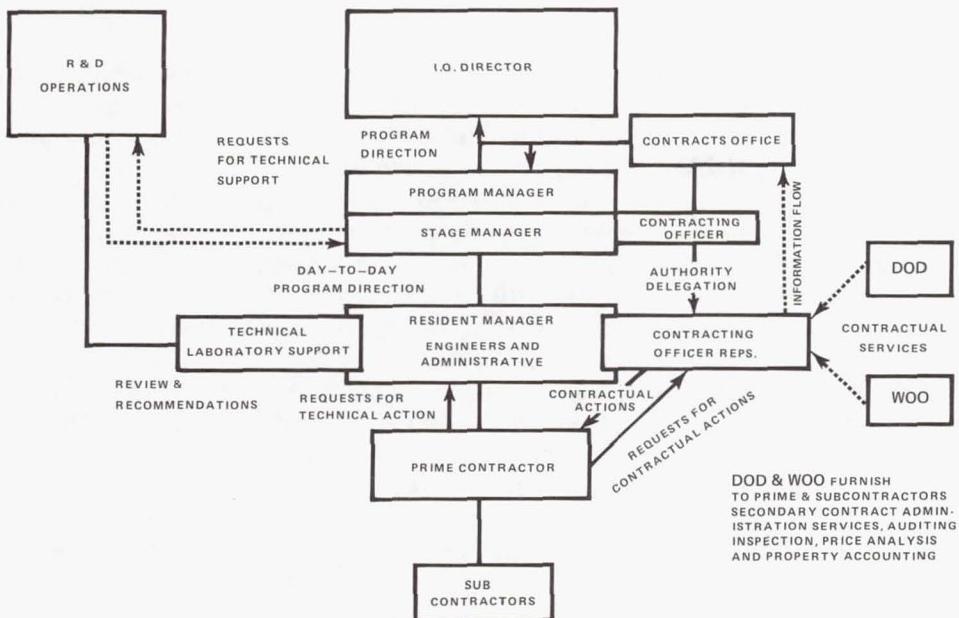
they should be allowed to go their own way after the contract was signed.³⁷ The longing for more freedom of action was evidently a legacy of the experience that most Saturn contractors had previously had with Air Force contracts. Huntsville had great technical competence; at certain managerial levels of design and manufacturing, grumped one highly placed contractor executive, Marshall maintained a one-on-one surveillance. The Air Force, he said somewhat wistfully, was "not in your pants all the time."³⁸ But Rees maintained that loose reins on the contractor had not always worked out well from the MSFC point of view. "Consequently," he said, "it became clear that close and continuous surveillance of the contractor operation was required on an almost day-to-day basis." The extent of the surveillance was proportional to the subtleties and problems of the program, its relative position in relation to the existing state of the art, and the extent of expertise possessed by MSFC. The contractor's reaction to this aspect of NASA monitoring was not favorable at first, but eventually this "penetration and monitoring" was perceived to be a mutual benefit characterized by the often repeated phrase, the "government-industry team." "Contractor penetration" was an important concept that ultimately involved the contractor's relationship with his own subcontractors.³⁹

One of the most interesting aspects of contractor penetration was the RMO approach. NASA could exert considerable influence on technical decisions that affected the managerial organization of the contractors. General Samuel C. Phillips, who directed the Apollo Program Office at NASA Headquarters, revealed this leverage during one of the program review sessions held at NASA Headquarters in 1964. He noted that various contractors had strengthened their organizations during the preceding year, "either on their own or due to appropriate influence by NASA."⁴⁰

Phillips's comment on the use of appropriate influence was an understatement, since MSFC could, and did, force contractors to change their modes of operation. In 1963, the development of the S-IVB was in its dual role as the second stage of the Saturn IB vehicle and as the third stage of the Saturn V. This duality posed something of a problem of interfacing for the S-IVB prime contractor, Douglas Aircraft Company. Discussing the S-IVB project during the 1964 program review, Lee James pointed out that MSFC management wanted to make sure that Douglas did "not see two faces at Marshall. It is important they see only one." As far as the contractor was concerned, the Saturn IB/S-IVB manager acted as deputy to the Saturn V/S-IVB stage manager, placing basic responsibility in the Saturn V Program Office.⁴¹

During his presentation, James spoke on the subject of "Saturn I/IB Launch Vehicles and Related Facilities," in which he noted that management constituted a "major part of the problem." Moreover, he continued, "a major part of that problem was considered to be with Douglas."

MSFC/CONTRACTOR RELATIONSHIPS



NASA's Manned Flight Awareness program made its mark in all major contractor operations (see diagram). This scene is in the Douglas plant; S-IVB stages are being fabricated and assembled under the banner on the far wall, "Saturn VIP," which in Douglas stood for their "Very Important People" who had made safety or quality assurance contributions.

STAGES TO SATURN

Douglas had never set up a project-oriented organization, James explained, and the management structure in operation never worked very well in any case. The crux of the difficulty seemed to be the company's Sacramento Test Facility (SACTO), set up as a part of the engineering manufacturing divisions, with ties to both Santa Monica and Huntington Beach. As a result, James said, there was no place "to pull their organization together" to make sure programs like the battleship test and the all-systems test evolved smoothly and logically. Management at MSFC stepped in to remedy the situation. James put it bluntly: "We forced Douglas to reorganize Sacramento into a separate entity." As a result, SACTO reported directly to the upper echelons of Douglas management, and MSFC was involved in the reassignment of Douglas's Deputy Director of the Saturn Program to the new position of Director of Sacramento Test Operations, a further benefit to the reorganization. To enable MSFC to operate from a stronger posture at Douglas, the office of the Resident Manager was strengthened, and a new person was brought in for the job. James said that over 90 applications for the position had been received, and he was pleased to report that "a very strong individual" had been chosen. In fact, the successful applicant was so eager to shoulder the responsibilities that he took a salary cut of \$8500. "I think we have found just the man we are looking for in order to give us the strength on the spot that we need," James concluded.⁴²

The policy of contractor penetration did not imply relentless meddling in the internal affairs or organization of the company. Indeed, most of the pressure applied by MSFC seemed to occur early in the program. Monitoring continued, but on a lesser scale. The initial problems were peculiar to the complicated requirements of getting "cranked up" for a new program such as S-IVB battleship testing, where MSFC, Douglas, and Rocketdyne (the engine contractor) were all involved. MSFC formulated a "start team" that used personnel from all three organizations. This special group coordinated and channeled early activities, and proved to be a successful approach in the S-IVB program. As the program gained momentum, the contractor assumed more responsibility. "We also recognized in the S-IVB program that Douglas is a major manufacturing organization and once they get rolling, they are a good organization," said James emphatically. "Our problem always is on the initial stages. We have made a major effort to concentrate on getting the first stage out the door, knowing we can trust a contractor like Douglas to follow on with the succeeding stages."⁴³

The technique of contractor penetration to maintain high visibility obviously generated some thorny issues in government-contractor relations. Nevertheless, MSFC felt that industry had a strong inclination to take control of the job and the funding and pursue the job with a minimum of government intervention. MSFC management believed this inclination allowed too much opportunity for slippage, unidentified

problems, and poor communications. Vigorous contractor penetration reduced these program difficulties; in the long run, the contractors seemed inclined to accept the penetration as a mutually useful aspect of completing a successful program. "The restiveness that stemmed from such close control was gradually dissipated very early in the Apollo program as the benefit accruing from the industry-government team approach was revealed," concluded Eberhard Rees.⁴⁴

Realizing the relationship between contractor motivation and success, the Saturn V Program Office implemented general NASA policy regarding contract incentives as a means of encouraging the contractor to perform at the highest possible level of endeavor. Most of the original contracts stipulated a cost-plus-fixed fee, useful in the early phases of a program when management had to deal with many unknown factors and close pricing was uncertain. After the R&D phase was well in hand and the unknowns were worked out, it became possible to adapt incentive- or award-fee provisions in all Saturn contracts except the S-II stage contract. The S-II contract eventually had limited award-fee provisions for management performance. The contracts for the lunar roving vehicle and the instrument unit were cost-plus-incentive fee (CPIF) from their initiation. The remaining contracts were changed in 1966 from cost-plus-fixed fee to cost-plus-incentive fee.

The incentive contracts were established in two portions: a comparatively modest base fee, and a segment of payments scaled to incentives. These scaled incentive fees were awarded in proportion to the contractor's success in meeting time schedules, cost allowances, and performance ranges. The incentive fee contract was judged to be most successful in cases involving hardware contracts where schedules, costs, and major milestones were fairly well established. The Saturn V Program Office considered the approach a successful alternative to fixed-fee contracts, because the incentive-fee contracts encouraged the contractor to meet commitments on hardware delivery and contributed to mission success.⁴⁵

RELIABILITY AND QUALITY CONTROL

Within the Saturn V Program Office, as in other MSFC operations, management paid special attention to the areas of reliability and quality control. The project offices viewed reliability as a significant element of basic design technique, and continued relevant procedures for judging the design of subsystems, components, and parts, as well as the overall stage design. This approach included techniques to evaluate the necessity for redundancy, criticality of numbers, and failure mode and effects analysis. Management also pursued an exceedingly active qualification test program, exposing components and subsystems to simulated flight loads under environmental conditions. This test was a major contributive

STAGES TO SATURN

factor to the success of the Apollo-Saturn program, although it was expensive. The hardware was costly, and rigorous testing of such a large portion of it meant that much of the hardware could not be used later as flight hardware. In some cases where funds were particularly tight, qualification tests were conducted at a reduced level, followed by intensive and exhaustive data analyses to extrapolate performance through various conditions of flight. The object was to be able to use such hardware on actual missions later on. In these instances, it was necessary to be careful not to overstress these future flight components, and to extrapolate data so as to avoid risks during the actual missions.⁴⁶

The problem of quality control was further affected by MSFC's reliance on the Department of Defense, which exercised quality control management in some of the contractor plants. In the mid-1960s, MSFC made an effort to increase its own quality control programs, particularly in the inspection of incoming vendor surveillance. Douglas, for example, evolved its own approved parts list; parts not listed were unacceptable in design specifications submitted by prospective vendors. Basic guidelines for the list came from MSFC documents, buttressed by information from the military, industry sources, and Douglas's own experience, and were substantiated by operational and test data in the course of the program. The approved parts list included such items as bearings, fasteners, switches, relays, transformers, wires and cables, capacitors, resistors, semiconductors, and fluid fittings. Among the tangle of parts required to make a rocket work, the pipes and tubing with their respective connections were expected to operate under extreme and rapid temperature change, shocks, low pressure, and intense vibration. All parts had to be flight weight and have the imprimatur of the approved parts list.⁴⁷

The Saturn V Program Office continued to monitor the activities of its own prime contractors, stepping in when necessary to advise changes. One such instance occurred in July 1964, when one of the welds of the S-IVB stage failed and the consequent rupture of the tankage caused the loss of the entire structural test stage. As a result of this incident, MSFC "caused Douglas to go into TIG welding with the higher heat input than the MIG welding that they were using in certain areas." MSFC technical personnel reported higher reliability after the change, and approved Douglas's revision of weld inspection procedures, which MSFC judged to have been somewhat weak.⁴⁸

In pursuing reliability and quality control, the project managers found that they had to exercise considerable diplomatic tact, making sure that the contractor had sufficient leeway to develop valid design concepts without overdoing it. "It is in the nature of experts that they become beguiled by intriguing technological problems," warned Eberhard Rees, and such beguilement could lead to excessive pursuit of reliability and performance. This situation was sometimes tolerable in industry, in the interest of better products for competition, but not in the space program.

It was necessary to be constantly on guard against losing simplicity—easy to do in the early stages of a program that was complex, large, and pressed by tight schedules. “Even when weighed in the balance against sacrifice of performance, design simplicity should be strongly favored,” Rees recommended, because more components and higher performance often increased the prospects for failure. Rees noted that “Project management has here a rather complicated task of putting the brakes on these tendencies without discouraging development of new technology and with it of highly inventive people.” Arthur Rudolph was adamant about this point, and put it even more succinctly: “Make it simple, make it simple, make it simple!”⁴⁹

In the quest for high performance, reliability, and quality control, incentive contracts constituted only one of a number of blandishments. Several techniques were employed by MSFC, including cash awards and special recognition for quality control, cost reduction, and other activities. At MSFC, the Saturn V Program Office cooperated with the Manned Flight Awareness Office in a program to inform and remind all workers in the Apollo-Saturn program about the importance of their work and the need for individual efforts. By means of awards and recognition programs, the Manned Flight Awareness concept became an effective incentive technique. The prime contractors also conducted special incentive programs, in collaboration with the project managers and RMO personnel. North American’s program was known as PRIDE (Personal Responsibility in Daily Effort), and Douglas had its “V.I.P.” campaign (Value in Performance). MSFC’s Manned Flight Awareness personnel and the contractors also participated in a program to make sure that vendors and subcontractors shipped critical spare hardware in special containers and boxes. These boxes were marked with stickers and placards imprinted with reminders to handle with particular care, because the hardware was important to the astronauts whose lives depended on the integrity of the hardware.⁵⁰

THE PROGRAM CONTROL CENTER

The Saturn V Program Office relied on a facility known as the Program Control Center as a focus for decision-making. The nature of the Saturn program, with contractors and NASA facilities scattered from coast to coast, presented a real challenge in codifying information for managerial decisions. As one Saturn V Program Office manager said, it was “essential that we had some way of making sure that we had pulled together all the facets of the program into an integrated program with good visibility. And that, I would say, has been probably the main purpose of this Program Control Center—to try to provide the program manager with that integrated visibility.”⁵¹

STAGES TO SATURN

The archetype of the Program Control Center was probably the "Management Center," developed in 1956 for the use of Rear Admiral William F. Raborn, Jr., during the Polaris program. To get ideas for Raborn's Management Center room, his personnel visited the Air Force Ballistic Missile Division in Inglewood, California, and, interestingly, the ABMA operation in Huntsville. The Polaris center was designed to avoid the look of a boardroom and was filled with 90 chairs facing a large motion-picture and slide screen in the front, and numerous charts hung on the walls around the room. The idea was to provide maximum visual capability of Polaris events in a briefing room.⁵² The Boeing Company elaborated this concept as a management tool during its Minuteman missile program for the Air Force. Beginning in 1959, a series of Boeing control rooms resulted in a style of visual presentations, by means of charts and audio-visual aids, intended to reduce the reams of management reports being used to monitor the progress of the program. The company activated such a control room at its S-IC (the Saturn V first stage) manufacturing facility at Michoud, near New Orleans, Louisiana, in 1964. In 1965, Boeing was awarded a contract by MSFC to develop an advanced control room management facility at Huntsville.⁵³ This became the Program Control Center (PCC) of Rudolph's Saturn V Program Office. Although the Marshall center's PCC looked somewhat like a boardroom, it became an unusually active facility. The conference table in the center of the room seated 14, and the movable chairs around the edges of the room raised its capacity to several dozen.

The PCC epitomized the managerial concepts of "management by exception" and "single threading." The technique of management by exception was based on the premise that the program manager should keep his number of contacts within manageable limits, and Arthur Rudolph relied heavily on his project managers to work with the contractors and solve various problems as they arose. "Within my Saturn V Program Office," Rudolph explained, "each project manager has wide latitude to exercise management actions just as long as these actions meet established technical performance requirements and schedule and budget constraints." Rudolph's control over the project managers went just far enough to ensure that performance, schedule, and budget guidelines were met, that interfaces were kept in repair, and that unintended redundancy was eliminated. "This policy of management by exception has enabled us to operate effectively and efficiently and has given my people the incentive to perform to their fullest capabilities," he said.⁵⁴

The PCC needed to develop a means of singling out special problems for more detailed analysis, including probable program impact, and to know exactly who was responsible for monitoring and solving problems. The concept of "single threading" provided graphic documentation for tracing a problem to a detailed position for assessment and determining a probable course of action to resolve it.⁵⁵ The means for

MANAGING SATURN

such analysis were embodied in the data organized for viewing in the PCC. Thus, the PCC was an arena for comprehensive displays for use by management—a focal point for collection and presentation of information concerning the status of the Saturn V program, and planned so as to provide displays for various levels of detail. This approach permitted managers to identify the problem, begin action for resolution, and monitor progress.

The PCC for the Saturn V Program Office was one of a network of such rooms located in the Apollo Program Director's office at Headquarters, at each of the three Apollo-Saturn NASA centers (Kennedy, Marshall, and Houston), at each of the prime contractors' offices, and at Mississippi Test Facility. The network allowed top management and other personnel to keep up with a myriad of activities, including logistics, astronaut training, scientific projects, selection of lunar landing sites, the worldwide tracking network, mission planning, and the mission itself. Each had the latest information and up-to-date displays for its appropriate job, including general Apollo-Saturn program information as required, along with a sophisticated communications system to accelerate the decision-making process.⁵⁶

The PCC provided two basic ways to display information: open wall displays and projected visual aids. The open wall displays were used to portray information that was updated and changed on a cyclical, day-to-day, or new-problem basis. Most of the display charts were constructed so that they could be moved in and out of position on horizontal tracks. They were marked by coded symbols so the viewer could tell at a glance if a project was lagging, ahead of schedule, or on schedule. Both the project offices and the staff-functional offices submitted data and maintained liaison with PCC personnel throughout the preparation and use of the display charts, and the offices were responsible for having proper attendance in meetings where their display material was to be discussed.

Each display carried the name of the individual responsible for the data. If the project office representative could not answer questions or supply additional information, the person to contact was immediately identifiable from the chart, and a quick phone call could make him—or the information—available during the meeting. Some charts concerned items being covered by what MSFC called the problem resolution system. The data indicated the criticality of the problem, the specific hardware or operation involved, the originator of the data, the identity of the "action manager," and the current status of the problem. Other charts showed aspects such as costs and technical data (weight, performance, and configuration management).

Rudolph always insisted on having a name associated with the charts. He wanted to work with a person, he said, not an anonymous office. Backing up the charts was a comprehensive set of "management matrices" in notebooks, listing all individual counterparts, by name, for all



MSFC's Saturn V Program Office operated out of this Program Control Center, rimmed with recessed, sliding status charts and double picture screens for comprehensive, up-to-the-minute briefing on progress and problems in the far-flung program.

major systems and subsystems of the hardware. The matrix pages included MSFC counterparts for Industrial Operations and R&DO, other centers, and the contractors. To find out why a valve did not work, the Saturn V Program Office could call each person responsible for the project, and not waste time calling the wrong office or waiting for an office manager to decide who could provide a competent response to a specific query.⁵⁷ Rudolph wanted a fast and accurate response to problems, and he usually got it.

For a long time, the rear of the PCC was dominated by a huge PERT chart (Performance, Evaluation, and Reporting Technique). PERT was a sophisticated and complex computerized system, with inputs beginning, literally, at the tool bench. Technicians on the floors of contractor plants around the country monitored the progress of nearly all the hardware items and translated the work into computer cards and tapes. Data for costs and schedules were also entered into the system. The PERT network was broken down into 800 major entities, and summarized 90 000 key events taking place around the country. PERT helped provide

MANAGING SATURN

the answers. If a gas generator exhaust line under test in California was showing problems, how would this affect the static test schedule at the Mississippi Test Facility (MTF), and a scheduled launch from Cape Kennedy? What would be its cost impact? How would it affect other hardware? What would be done about it?⁵⁸

Like the PCC network, PERT received a strong impetus in the Polaris program in the mid-1950s.⁵⁹ During the early phases of the Saturn program, MSFC management regarded PERT as a very successful effort. At a NASA Management Advisory Committee conference in 1964, von Braun said that PERT was the best source of information available on the status of hardware programs. The PERT network did not catch everything; for example, a parts problem on Boeing's S-IC-T (test stage) had been missed. Still, MSFC managers in 1973 recalled PERT as one of the most useful management systems, although the PERT network was phased out about the time of the launch of the first Saturn vehicle (AS-501) in the winter of 1967. One reason was that PERT was tremendously expensive. A large number of people within NASA and from the contractor's special computer programs were needed to make the network perform adequately. "It has some use as a preliminary planning tool," said R. G. Smith, a Rudolph successor, "but when tens of thousands of events per stage are used, it is difficult to analyze, usually lagging in real time usefulness, and subject to manipulation to avoid exposure of real problems."⁶⁰

During launch operations and special activities, the PCC was linked to KSC and Houston by closed-circuit television. Although conferences in the PCC were not televised by closed circuit (because of space limitations and technical problems), the communications arrangement permitted discussions in the PCC to be heard instantaneously at NASA Headquarters and other centers. The ceiling of the PCC room was studded with extrasensitive microphones, so that anyone at the conference table in Huntsville could interject a comment or respond without leaving his seat, and nobody had to wait until a speaker somewhere else had finished. When a speaker in Huntsville was making a presentation, conferees in Houston or Cape Kennedy could freely respond. In addition, conferees visually followed the presentation at other locations by means of viewgraphs supplied beforehand by the speaker. The viewgraphs were transmitted by Long Distance Xerox (LDX) system on a leased telephone circuit. Using standard typewriter-size sheets, the LDX line transmitted high-fidelity copies at the rate of about two copies per minute. After receipt at the other end, personnel used them to reproduce the numbered viewgraphs, shown in sequence as requested by the speaker. The fast response of the LDX system permitted up-to-the-minute documentation, and if there was not time to prepare new viewgraphs, conferees at the other locations could be supplied with regular Xerox copies instead. The ability to exchange such material meant that informed decisions could be made

STAGES TO SATURN

while the meeting was in progress. Rudolph insisted on detailed viewgraphs, in words as well as diagrams, so that the viewgraphs could serve as minutes of the PCC conferences.⁶¹

SATURN MANAGEMENT: A MATTER OF "STYLE"

The Saturn V program, and the vehicle itself, was enormously complex. Counting everything from nuts, bolts, and washers to transistors and circuit boards, the Saturn V booster alone had something like 3 000 000 parts (in addition, the command and service modules had 2 000 000 parts; the lunar module 1 000 000).⁶² Manufacture of the rocket stages involved thousands of contractors and the expenditure of millions of dollars per week. The scope and cost of the effort raised the obvious question: how did NASA do the job? and, more specifically, how did MSFC keep tabs on a multimillion-piece monster? Another question was: is it possible to point to a unique style of management in the lunar landing program?

James Webb, NASA Administrator from 1961 to 1968, warned that in large-scale endeavors such as the Apollo-Saturn program, managers needed to be especially flexible because many "unpredictable difficulties" as well as many "unanticipated opportunities" would crop up. Many traditional management concepts were not applicable because the large-scale R&D endeavor was so dynamic. Managers needed to have a sound foundation in basic management principles, but also needed to be able to work in an environment where the lines of communication crisscrossed and moved in unusual directions, and where the job was not always exactly defined in the beginning. The successful manager had to do more than understand the organizational framework backward and forward. He had to grasp the total dimensions of the effort and define his role in the task. In this context, successful aerospace managers availed themselves of existing fundamentals of management, whatever their source of origin, and raised them to a higher degree of refinement in complex activities involving high technology.⁶³ One sophisticated observer characterized NASA's managerial contributions:

To accomplish the moon landing within the time set by President Kennedy, Apollo's designers deliberately hewed to techniques that did not reach far beyond the state-of-the-art in the early Sixties. The really significant fallout from the strains, traumas, and endless experimentation of Project Apollo has been of a sociological rather than a technological nature: techniques for directing the massed endeavors of scores of thousands of minds in a close-knit, mutually enhancing combination of government, university, and private industry.

Apollo has spawned an intimate and potentially significant new sociology involving government and industry, an approach that appears to stand somewhere between the old arsenal concept favored by the Army and Navy and the newer Air

Force concept that depends heavily upon private corporations to manage, develop, and build big systems. The NASA approach combines certain advantages of each, while enhancing the total abilities of both private and government organizations.⁶⁴

In the Saturn program, successful management style was a blend of the decades of experience of the original von Braun team in Germany and management concepts from the Army, Navy, Air Force, other government agencies, and private industry. As the early SSO began to elaborate its relationships with prime contractors, Air Force concepts of configuration management became more conspicuous. During the evolution of the Saturn program at MSFC, the Army's arsenal concept was inherent in the R&DO arrangement, although its premier role was altered as a result of 1963 reorganization. Both the Army and the Air Force contributed key managers.

The Air Force influence was pervasive, from the Headquarters level on down. George Mueller, Associate Administrator for Manned Space Flight, came from private industry (Space Technology Laboratories), but he had worked with several Air Force missile programs, including Atlas, Thor, Titan, and Minuteman. His deputy for the Apollo-Saturn program, Brigadier General Samuel C. Phillips (USAF), brought skills in configuration management and logistics management that had been acquired during the Minuteman effort. At MSFC, Robert Young, the first IO director, had executive experience with an industrial contractor (Aerojet) that also had been involved in Air Force missile programs. Young was succeeded by General Edmund F. O'Connor (USAF). The influx of other Air Force officers in 1964 has already been noted. On the other hand, numerous Army officers left ABMA to join MSFC, including Lee James, who served at one time as the Saturn I-IB Program Manager, worked at NASA Headquarters, and later was head of the IO division. James replaced General O'Connor, who had returned to the Air Force. From NASA Headquarters, Mueller's GEM Boxes constituted a significant managerial technique in the Apollo-Saturn program, and MSFC elaborated upon its own concepts of working groups, management matrices, and (borrowing a bit from the Polaris program) the Program Control Center.⁶⁵

From his vantage point as an active manager in the Army and NASA and as an observer of Air Force management, Lee James paid special tribute to the R&DO laboratories that he believed gave MSFC "unusual depth." The laboratories were one of the outstanding aspects of MSFC management under von Braun. "It's hard to make them work in the government," James said. "That is a unique attribute."⁶⁶ Although von Braun emphasized the overriding authority of the program and project offices in their relationships with the laboratories,⁶⁷ contacts were not always unruffled. During a session with Headquarters executives in 1964, both Rees and von Braun agreed, "The project manager is definitely in

STAGES TO SATURN

the driver's seat on project management matters. R&DO provides technical knowledge in depth to solve the technical problems, but at the same time carefully avoiding any interference with contract management. The stage manager is the sole contact with the contractor." Reading the minutes of the meeting a few days later, one of the top managers in the Saturn V Program Office expressed his frustrations in an astringent comment scribbled in the margin: "Wouldn't it be good if this were so! Top mgt. needs to say so in a policy statement and then enforce it."⁶⁸ The situation festered for several months, until von Braun issued a detailed directive to the heads of both Industrial Operations and R&DO, in which the authority of Industrial Operations (and the Saturn V Program Office) was asserted in explicit terms.⁶⁹

Although it is difficult to document the specifics, relationships between Industrial Operations and R&DO were often uneasy. As recalled by an observer from within the Saturn V Program Office, one form of managerial assertion was out-and-out harassment. A stage manager might call up a laboratory chief in R&DO and complain about the lack of activity or lack of cooperation from the counterpart personnel in the laboratories. Other methods included pointed reminders about directives from the program manager's office, a claim to be acting at the behest of the program manager, the use of technical knowledge that others would hesitate to contradict, and outright exposure of deficiencies.⁷⁰

The same techniques were also applied within the Saturn V Program Office, as the staff-functional managers (the GEM Boxes) jostled with the stage managers. It must be remembered that Rudolph considered his functional managers to have as much authority as his stage managers. This approach was unique to the Saturn V Program Office; other program offices tended to allow the hardware managers greater authority. Rudolph's arrangement was deemed necessary, however, to maintain vertical control over the stage elements of the Saturn V, especially since the stage managers were sometimes considered to manifest a parochial attitude about their own activities.⁷¹ The role of the functional managers was spelled out in a program element plan document:⁷²

Establishment of managers for functional areas is an important management concept used in the Saturn V Program. These functional areas, e.g. Program Control, Systems Engineering, Test, may be considered as "vertical slices" of the vehicle which result in stages, or "hardware" items. The functional managers are responsible for planning, coordinating and directing their areas, insuring that a single thread of effort is carried from the highest level of Apollo management in Washington through the Center level and into the prime contractors.

The Saturn management concept consistently put a premium on visibility, epitomized by the Program Control Center in the Saturn V Program Office. Webb, who prided himself in the development and exercise of managerial expertise, was amazed by its conceptual format

and versatility. During a visit to MSFC in 1965, not long after the activation of the PCC, Webb was given a thorough briefing on the facility by Rudolph and Bill Sneed, who was head of the Program Control Office at the time. Following the briefing, Webb addressed a select group of MSFC personnel, and was obviously enthusiastic about the PCC concept. "I saw here in the hour before you arrived," he exclaimed to his audience, "one of the most sophisticated forms of organized human effort that I have ever seen anywhere."⁷³ Webb's remark was a special compliment to Huntsville's PCC; Huntsville later became the model for NASA's Apollo Program Office in Washington as well as for other centers and prime contractors. Over a period of years, at Webb's behest, a stream of executives from government and American and foreign industry tramped through the PCC. The Saturn V Program Office also received inquiries by telephone and letter from a wide spectrum of sources, including the famed design group of Raymond Loewy and Associates. A former member of the Polaris management team once visited the PCC and came away thoroughly impressed. "This chart room of yours is an amazing place," he said to Rudolph. "I used to think the ones we had in the Polaris program were good, but this puts us to shame."⁷⁴

The Marshall center's organization experienced several adjustments after 1969 in response to new directions in NASA programs. By 1972, the IO segments operated as individual program offices and reported directly to the head of the center. The R&DO laboratories were set up as the Directorate of Science and Engineering, along with several other directorate organizations. Under the new scheme, the Saturn Program Office contained all the various stage and engine offices for the Saturn IB and Saturn V, and also included the PCC. Many of the individuals associated with the original Saturn V Program Office took new positions involving Skylab, the Space Shuttle, and other projects. Following the Apollo-Soyuz Test Project in August 1975, NASA planned no more launches of the Saturn class of vehicles, and the Saturn Program Office was finally dissolved.

SUMMARY

MSFC management strongly reflected the tradition of the "dirty hands" approach begun by the von Braun team at Peenemuende and continued during the operations at ABMA. The organizational structure and influence of the technical laboratories was another vestige of rocketry work from the pre-World-War-II era. The pronounced shift toward managerial functions after the 1963 NASA-MSFC reorganization enhanced the prestige of Marshall's Industrial Operations component, and the influence of Air Force concepts of missile management was

STAGES TO SATURN

evident in the extended tenure of General Edmund F. O'Connor as its head.

The crux of Saturn V management was Arthur Rudolph's Saturn V Program Office. Rudolph's missile management skills had been enhanced by the Redstone and Pershing programs; as a Peenemuende veteran, he could also relate effectively to von Braun and other key MSFC managers of similar backgrounds. Within Rudolph's organization, the "GEM Boxes" provided an effective and crucial link to offices at NASA Headquarters and developed and applied various management systems serving Marshall and the contractor; the Program Control Center provided the means for visibility and accountability in the Saturn program.

It is impossible to pinpoint any single outstanding or unique management concept that led the program to success. The NASA-MSFC "style" seems to be more of an amalgam of various concepts, although these concepts were refined for the unique scope and complexity of the Saturn program. In general, the government-industry partnership was notably successful, and the in-house capability at MSFC was highly effective in monitoring contractor performance and providing backup skills and facilities. The organization and operation exhibited by the Program Control Center lent a theme of "visibility" to the Saturn program. Among the many managerial tasks, logistics was a major effort.

10

The Logistics Tangle

Lunar flights were critically dependent on the "launch window," when trajectories of the orbiting moon and the space vehicle were compatible. Crucial slippages in preparation time were avoided during the final weeks prior to launch so that liftoff occurred during the "launch window." Schedules and deadlines extended back to the production process of rockets and their complementary equipment—a process that was nationwide and exceedingly complex. Components from thousands of contractors and subcontractors not only had to be completed on time, but all components had to arrive on schedule at one of the major centers so that units could be assembled and thoroughly checked out. The units were then shipped to Cape Kennedy for stacking on the flight vehicle. The Saturn V required 56 railroad tank cars to supply its necessary propellants. The various stages for one launch vehicle spent up to 70 days in transit at sea before arriving at Cape Kennedy, while the S-IVB and the instrument unit arrived as airborne cargoes. In the background were over 20 000 contractors and subcontractors who supplied hundreds of thousands of individual parts for the Saturn V. In 1966, Arthur Rudolph, speaking as the Director of MSFC's Saturn V Program Office, commented succinctly, "Not the least of the problems in the Saturn V system is logistics."¹

Wernher von Braun, Rudolph's superior at Huntsville, pointed out two special reasons for emphasizing logistics. First, the costs of logistics might run to as much as one third of the entire launch vehicle program's budget. Any improvement, he stressed, saved money fast. Furthermore, von Braun said, logistics seemed to be taken for granted too often, and this led to troubles. By 1966, the Saturn launch vehicles had been

STAGES TO SATURN

launched successfully 13 times, and good logistics was an important factor in this record of success. Still, there were occasional logistical tangles, and "there have been some awfully close calls," von Braun warned. Although the term logistics could be applied to many functions such as financial analysis and procurement, the word as used during the Saturn program applied to activities in direct support of hardware development, testing, and mission operations. This task included spares provisioning, inventory management, maintenance and maintainability, training and technical support documentation, transportation, the supply of propellants and pressurants, and the management, coordination, and evaluation of the entire process.²

THE ORIGINS OF SATURN LOGISTICS

In retrospect, the need for a logistical program seems logical and obvious, but it was slow to develop; the lack of such a program hampered the Saturn program for several years. When Congress passed the Space Act in 1958, the U.S. manned space program relied primarily on rocket vehicles derived from the nation's military ballistic missile programs. Despite their internal complexities, the Mercury and Gemini spacecraft were manageable under existing conditions, and the Air Force provided the requisite support functions for the launch vehicles and related logistical phases. The Apollo program changed the ground rules, because NASA intended to supply its own launch vehicles, but lack of time and money stalled the implementation of a logistical setup for the Saturn launch vehicle program.³ In the early phases of Saturn program planning, many officials felt that there was no need for military-style "launch vehicle system logistics" based on rocket weapons because NASA did not have the problems of large numbers of rockets and dispersed launch sites. Lamentably, this seemed to lead to a second assumption: since a weapon logistical system seemed inappropriate for NASA, a consensus evolved that there was no need for a logistical program at all.⁴ This weakness in reasoning stemmed partially from differences in the nature of the launch vehicles. NASA planned to launch a limited number of vehicles at fixed intervals and from one point, contrasted with a theoretical military situation where many launches occurred at unscheduled times from widely scattered launch sites or field positions. In a national defense situation, numbers of missiles and unanticipated circumstances required an elaborate logistical backup. Troops in the field were essentially unschooled as engineers and relied on a logistical array of technical manuals, parts, spares, and rigidly scheduled maintenance. Saturn personnel, on the other hand, included a high percentage of engineers. They did not have to rely on military procedures but could refer immediately to engineering drawings and work out an appropriate "fix"

THE LOGISTICS TANGLE

on the spot, supported by conveniently accessible laboratories and machine shops at the launch site.⁵

The hopeful assumptions about the launch vehicles did not suffice. Factors that required logistical management included the size and complexity of vehicles, the wide geographic dispersal of launch and test sites, the pace of the program, the armies of technicians involved, and the number of suppliers around the country. "Misinterpretation then, caused neglect of an integrated logistics program," Rudolph admitted. "Thus we . . . created for ourselves a considerable problem by not allowing enough thought and planning toward logistics at the very outset." Theoretically, once administrators pinpointed a basic weakness in the Saturn program managerial structure, it should have been fairly economical to borrow some techniques of weapon logistics and adapt them to NASA's requirements. Comprehensive programs existed for the Minuteman and Pershing programs, but the logistics for an older, smaller rocket did not always prove adequate for a newer, larger one. As Rudolph observed, "I am not at all sure that logistic support of a launch vehicle program with its high rate of advancement in the state of technology and its associated highly complex ground support equipment is not more difficult than logistic support of a weapons system."

Further difficulties emerged as NASA management moved belatedly to establish an adequate logistical program. As problem areas became identified, additional funds to resolve the problems simply did not exist. When systems analyses indicated badly needed changes in logistics, the program manager had to take some sort of corrective action with existing funds. It came to making tradeoffs; the program manager, began to rob Peter to pay Paul and sometimes found himself in a dilemma. As Rudolph phrased it, "how much of a calculated risk can he afford to take"? In 1961–1962, Saturn V managers from MSFC and personnel from the Apollo Program Office at NASA Headquarters initiated a series of "intensive, accelerated studies" to bring the logistical picture into focus. Essentially, the goal was to update the logistical organization to fit the prevailing status of vehicle development and the availability of funds. "This agonizing reappraisal lasted over many months," Rudolph recalled, "but in this way, we were able to tailor tightly, I repeat, tailor our logistical program to meet the essential requirement of each stage, yet stay within budget limitations."⁶

Unsnarling the logistical tangle within the existing budget included the reeducation of the program managers and program personnel throughout the organization. Brigadier General Edmund F. O'Connor, Director of Industrial Operations at Marshall, emphasized the general lack of attention to logistics and misunderstandings about it in the early years. He believed that no visibility existed. "In other words," O'Connor continued, "we were having the same kind of trouble with logistics that we had with documentation, reliability, and the like. We had a serious

STAGES TO SATURN

communications problem, no logistics baseline, no logistics thread running through the entire program.”⁷

The outcome of this reevaluation was a formally organized logistical program that would keep logistical requirements up to date and that would hopefully avoid future problems. As the new plans emerged, NASA managers realized that the logistical programs of the contractors were also unclear. No one knew if contractor progress had achieved desired goals or if problems existed. Under the new regimen, Saturn V contractors began formulating logistical progress reports, and all developments were plotted against logistical control charts. In addition, each of the hardware managers acquired a logistical manager, a move that reflected the increasing concern and attention to the problem. Rudolph installed an overall logistical manager in his office to keep tabs on the lower echelons and the contractors, as well as on the MSFC laboratories in Huntsville.⁸

NASA's logistical management finally crystallized by 1963. Much of the push to reorganize the logistical format came from Stan Smolensky of NASA Headquarters and from Eberhard Rees, Deputy Director—Technical, in von Braun's office at MSFC. At the top of the logistical organization, NASA set up a Logistics Management Office at the staff level in the Office of Manned Space Flight (OMSF) in Washington. This new office reported directly to the Apollo Program Manager at OMSF and integrated the overall Apollo-Saturn support programs. For the Saturn launch vehicles themselves, MSFC organized a Project Logistics Office which reported to the Director of Industrial Operations. This office functioned both at a staff level and in an operational capacity, and acted in close cooperation with the respective program managers within the Saturn program as well as with the R&D laboratories at Marshall. The R&D laboratories had the technical responsibility for the development of much of the launch vehicle's systems and supporting hardware. For example, the Test Laboratory did considerable investigation of the special purpose vehicles, and the Astrionics Laboratory designated an individual to cooperate on work involving the instrument unit. Because many parts and components were being produced by the factories and the vehicles were taking shape, the project logistics office had to decide whether to repurchase or switch parts if a manufacturer decided to close down a particular operation or start up a different product line. This kind of situation meant that Marshall's personnel who were involved in the quality and reliability aspects also became part of the logistical organization. With the Project Logistics Office in operation in Huntsville, Houston's MSC relied on MSFC's growing capability for moving the command module, service module, and other large bits and pieces of spacecraft hardware around the country. As for logistical requirements emanating from the launch site in Florida, John C. Goodrum, head of

THE LOGISTICS TANGLE

MSFC's Project Logistics Office, remarked that "Kennedy always considered themselves a logistics-oriented center," with internal administrative channels to handle the job, although Marshall occasionally provided transportation for KSC.⁹

The cooperative aspects of the logistical program included the Department of Defense, which supplied some of the propellants and pressurants for the Saturn program. Some cryogenic production plants were jointly operated under the auspices of the Department of Defense and NASA, and MSFC monitored the specifications and construction of other plants around the country. By 1965, the major plants were in operation to supply cryogenics for the rising tempo of Saturn testing and launch operations. This capability was especially important for liquid hydrogen (LH_2). The space program helped raise the production levels to 190 metric tons per day, with the Saturn program absorbing up to 95 percent of the nation's total capacity. Once a plant became operative, NASA and MSFC were eager to coordinate its production with an active test and flight series, because increased LH_2 consumption was a way to save money. Producers established a price for their product that was in direct relation to the volume sold. In the early 1960s, liquid hydrogen was about \$20.00 per kilogram, but the price dropped to around \$2.20 per kilogram for 450 kilograms, 45 to 65 cents per kilogram for 2250 kilograms, and leveled off at around 35 cents per kilogram for higher volumes. Fortunately, MSFC "never got pinned" to the \$20.00 curve, Goodrum remarked, but the space agency paid some fairly high prices for liquid hydrogen from time to time. For transportation of assorted cryogenics, MSFC relied on fleets of trucks, mostly from commercial carriers; the Air Force lent occasional support.¹⁰

By 1966, Rudolph felt that the logistical problem had been controlled, and he confidently announced that the first Saturn V launch, early in 1967, would get off on schedule early in the coming year. The success in coping with the logistics of the launch cannot be underestimated. A comparison of PERT figures indicated a total of 40 000 events for the contractors working on the three stages and the instrument unit. For the ground support equipment (GSE) managers, over 60 000 events needed to be tracked. The components for ground support were manufactured throughout the United States and arrived at test sites and KSC by every conceivable means of modern transportation. Rudolph remarked that it was virtually impossible to illustrate graphically the full GSE logistical program and harder still to describe it.¹¹

The GSE delivery requirements had many parallels in the transport logistical requirements for the various rocket stages of the Saturn program. The development of this phase of Saturn logistics also involved a transportation network from coast to coast and relied on a wide spectrum of transport equipment.

STAGES TO SATURN

TRANSPORTERS: THE ROLL-ON/ROLL-OFF CONCEPT

Because the Saturn vehicles were originally designed for the utmost in vehicle integrity and manned missions, it would be inadvisable to degrade the integrity of Saturn components by using inferior transport modes and techniques. Rocket stages were transported thousands of miles and experienced hundreds of hours of constant vibration. There was always the possibility of damage to welded joints and seals, as well as to delicate components that were manufactured to very high tolerances. On arrival at Cape Kennedy, additional checkout tests frequently exposed a problem that could be traced to the transportation sequence. The logistics of rocket stages were not to be taken lightly.¹²

As early as 1959, personnel at ABMA began to study the problems of transporting boosters from the manufacturing area to the test stands and the problem of the long journey from Huntsville to the Atlantic Missile Test Range in Florida. Early proposals considered using existing transporters devised for Redstone and Jupiter missiles, but this equipment proved to be too small. To carry the larger Saturn series on Redstone-Jupiter transporters, investigators discovered they would have to disassemble and remove engines and associated equipment, then replace the engines each time the complete vehicle moved from manufacturing to testing areas. This process was repeated during shipment to the launch site. Engineers warned that such frequent reassembling would compromise the reliability of the vehicle.

As a second proposal, planners envisioned a gargantuan BARC-style amphibious vessel. The acronym came from Army nomenclature for an amphibious machine in military inventory at the time: Barge, Amphibious, Resupply, Cargo. The Army used BARCs for over-the-shore delivery of heavy tanks and other cargo, and this apparently served as the inspiration for an enormous BARC to transport Saturn rockets. This unit would pick up a Saturn vehicle at the manufacturing area, carry the vehicle to the test site and reload it after tests, and then the BARC would lumber overland and plunge into the Tennessee River. After cruising down the Tennessee and the Mississippi rivers, the ponderous BARC would churn through the Gulf of Mexico, clamber onto the Florida coast at Cape Kennedy, and move directly to the launching pads. The BARC concept was eventually scrapped. The shallow draft raised doubts about its seaworthiness in the Gulf, and its dimensions and difficult maneuverability would necessitate major modifications to existing buildings and manufacturing areas to accommodate the transporter alone. The engineers concluded that it would cost \$5 000 000 and would not be operational for four years. The ABMA study recommended the construction of towable transporters for the Saturn vehicles and planned to use proven, seaworthy vessels on the waterborne leg of operations.

THE LOGISTICS TANGLE

In October 1959, the Advanced Research Projects Agency (ARPA) gave the go-ahead to the Army Ordnance Missile Command (AOMC) to begin engineering studies on the Tennessee River for dock facilities that would be conveniently accessible to the manufacturing complex at Redstone Arsenal. By December, AOMC received further authorization from ARPA not only to construct the docks but also to begin designs for a barge to carry the oversize boosters to the launch site at Cape Canaveral. The engineers decided to equip the dock areas with electrical winches for a roll-on/roll-off operation that would use the ground transporter to wheel the stage aboard the barge, ride with it to its destination, and wheel it out again. This operation promised the least strain and damage to the stage during the strenuous handling and transportation phases.¹³

The size of the Saturn I first-stage boosters promised some headaches when the time came to move completed stages around the manufacturing areas and between the ships and the static-firing areas of Redstone Arsenal. The Saturn engineers in Huntsville devised a solution to the problem. For the final assembly of the Saturn I first stage, workers used a pair of huge circular assembly jigs to position the cluster of one center tank and eight smaller tanks around it. These assembly fixtures at either end of the rocket then became the load-bearing structures for transportation. After the completed booster was raised with huge jacks, wheel and axle assemblies were positioned at each end. With the stage lowered onto these assemblies, they were affixed to the assembly jigs, which now became support cradles for towing the stage. The wheel assemblies, using aircraft tires, were designed for independent braking and hydraulic steering. The transporter was towed by an army truck tractor at five to eight kilometers per hour through successive phases of checkout and test. NASA also used the transporter for loading and unloading the stage from the barges that carried it from Huntsville to the launch site on Florida's east coast.¹⁴

For the S-IC first stage of the Saturn V, MSFC's Test Laboratory designed a similar transporter in 1963. The S-IC transporter used a modular wheel concept, based on a two-wheel, steerable unit and clustered to comprise two dollies fore and aft—a total of 24 wheels. The wheels, similar to the 24-ply tires for earth-moving equipment, stood about as high as a man. Each modular pair of wheels incorporated a separate system for power steering, with all systems of a particular dolly interconnected by a computer to correlate the steering angles for all wheels in unison. Since the dolly units could be steered to $\pm 90^\circ$ from the axis of the transporter, the entire rig and its load could be maneuvered sideways, into, and out of checkout bays and test areas. MSFC used a modified Army M-26 tank retriever as the tractor unit for towing the S-IC and its huge transporter. The M-26, a 179-kilowatt (240-horsepower) model weighing 55 metric tons, included 27 metric tons of water ballast

STAGES TO SATURN

to cope with the counterweight of the transporter. The total length of the tractor and transporter unit came to about two-thirds the length of a football field and was capable of rolling along at eight kilometers per hour. In theory, the driver in the tank retriever's cab was in charge of the direction of travel, but in practice, he acted as a coordinator of a crew of other drivers and transporter personnel. When the S-IC transporter rig "hit the road," its entourage included a cluster of observers who walked along at each corner of the vehicle and alerted the driver coordinator positioned in the front of obstacles and clearances that were blocked from his view. The driver in turn relayed instructions to drivers on the transporter who were riding in cabs front and rear and who could manipulate the massive fore and aft dollies as required. Before taking on an actual stage, the entire crew trained throughout the MSFC complex on a tubular S-IC simulator that was built to the dimensions and weight of the actual stage.¹⁵

The size of the stages aboard the transporters and the combined loads they represented created some unique problems in hauling them across country. At Huntsville, highway engineers laid out a special roadway stretching 13 kilometers down to the docks on the Tennessee River. At Michoud, another Saturn roadway included the length of an old airstrip that lay between the manufacturing complex and the docking area for the barges. In California, where the Douglas and North American contractor plants were situated in urban areas, the state cooperated in granting special permits for the use of public highways for moving the S-II, S-IV, and S-IVB stages. These stages, though smaller than the S-IC, nevertheless presented special difficulties. Douglas, the

The first S-IC flight stage is cautiously towed through Marshall Space Flight Center on its way to the adjoining Tennessee River and its barge transportation.



THE LOGISTICS TANGLE

manufacturer of the S-IV and S-IVB stages for the Saturn I and Saturn IB, became the first major West Coast contractor to encounter such inconveniences. As the S-IV second stage of the Saturn I began to take shape in 1960, transport problems became pressing. A Douglas executive, H. L. Lambert, said that the problems of handling and transporting Saturn S-IV stages had reached the point where such considerations threatened to impose limits as a design factor.¹⁶

Each stage followed distinctive logistical patterns. After manufacture in California, the S-II traveled to the Mississippi Test Facility (MTF). The S-IC stage, manufactured at nearby Michoud, was also tested at MTF. Both stages, for all their prodigious bulk, could be transported with comparative ease via seagoing barges that used the extensive river and canal systems constructed around the Michoud and MTF facilities. After testing, barges once more carried the S-IC and S-II stages (and earlier S-I and S-IB vehicles) to Cape Kennedy. Logistical patterns for the S-IV and S-IVB were more complex. S-IVB was smaller than its companions and presented some unique handling difficulties in moving it through an especially congested area of Los Angeles to the shipping facilities. Difficulties were also encountered in loading the stages for a barge trip and delivering the stages further north and even further inland to the Douglas test facilities at Sacramento.

Customized apparatus for handling and transportation of the S-IV and IVB stages was paralleled by "customizing" the eventual routes to test and reshipment facilities. Although logic compelled logistics engineers to opt for canals and seaborne transportation instead of land transport, the overland mode still had to be used. The overland mode was the only way to move a stage from the manufacturing areas to the loading docks for the canal and seaborne segments of its journey. Douglas and NASA personnel in California began negotiations to move a 27 000-kilogram load on roads, subject to the various jurisdictions of state, county, and city. The planning and coordination took days. Fortunately, cooperation of local law enforcement organizations expedited the task, and flagmen from railroads in the area agreed to special duty when the stage and its accompanying entourage approached railroad crossings. Commercial firms that operated vans and various truck equipment, as well as local school districts with extensive bus schedules were called into consultation on the logistics of overland rockets. Because the rocket stage spread across all available lane space and the shoulders of the road, no parking space remained. Vehicles waited at roadside until the stage transporter moved by. Regular auto traffic could be rerouted, but bus lines and cartage business on normal schedules had to reroute their trips more carefully. The stage and transporter spread up as well as out, so utility companies agreed to raise (or even bury) their lines when no practical alternative routes seemed feasible. All other encumbrances along the right of way were eliminated

STAGES TO SATURN

along the final route. Finally, Douglas had the responsibility to coordinate the remaining myriad travel arrangements. NASA representatives cooperated with various military personnel on sea transport, while all three elements (Douglas, NASA, and the military) kept in touch on times of arrival and departure, interior schedules, proper support equipment to load and unload the cargo, and additional problems.

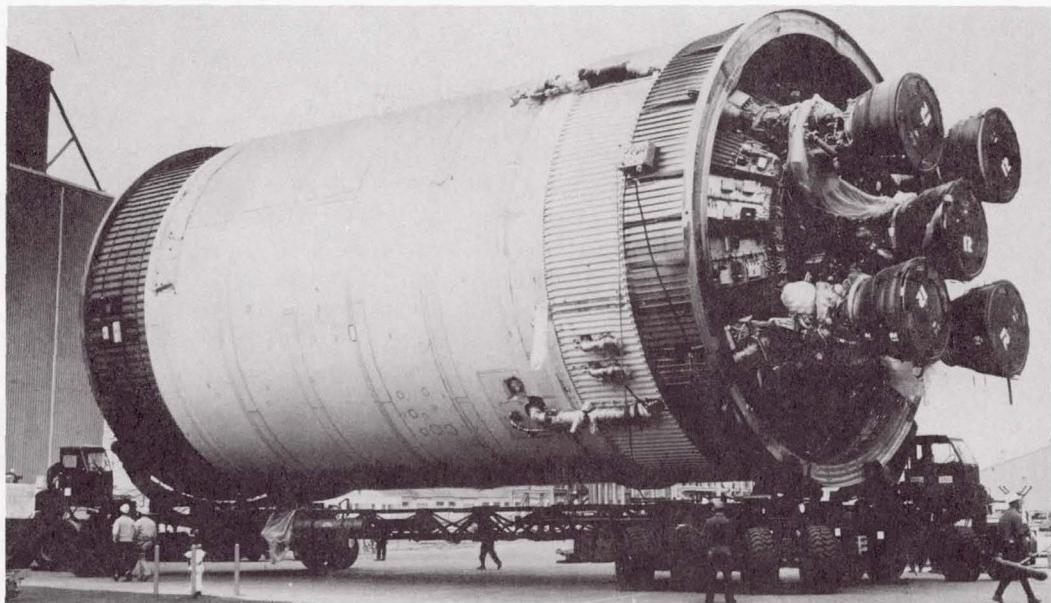
Inevitably, complications arose. Early in the S-IV program, a stage enroute from Huntington Beach to Santa Monica for transfer to a barge collided with one of nature's denizens. H. E. Bauer, then a senior S-IV manager with Douglas, easily recalled the novel circumstances. It happened early in the morning, with the loaded transporter creeping at 6.4 kilometers per hour. "At that speed nothing much should happen," Bauer reminisced, "but, incredible as it may sound, we did run over a very mature and ripe skunk." By a stroke of luck, the stage itself escaped unscathed, but the transporter remained a large, odoriferous problem—"we had a 23½ ft. wide, 46½ ft. long, 22 000 lb. skunk on our hands." With other missions pending for the one-of-a-kind transporter, the Douglas Aircraft Company chemists who devised an effective deodorizer ranked high on the list of unsung heroes of the Saturn program.¹⁷

Ground transport of North American's S-II stage, manufactured at Seal Beach, proved to be less difficult. The Seal Beach complex was only a few kilometers from the Navy's harbor at the Seal Beach Naval Weapons Station, and a broad, four-lane highway facilitated movement of the S-II from the manufacturing area to the docks, although all local traffic had to be stopped during the operation.¹⁸

The S-IV, S-IVB, S-IC, and S-II stages acquired miscellaneous customized accessories for logistical operations, including access kits. The size of the S-IC permitted a much more elaborate panoply of tiered and balconied work platforms, installed inside and out. The S-II access equipment resembled that of the S-IV and S-IVB, a work platform which moved up and down an internal tunnel inserted through the center of both the oxidizer and fuel tanks. Movement, shipment, and accessories for the Saturn's engines relied on more conventional means. Early in the 1960s, after preliminary static tests at Edwards Air Force Base in California, F-1 engines were flown to Huntsville by the U.S. Air Force Military Air Transport Service aboard C-133B cargo planes. Beginning in 1967, the engines arrived at Michoud by truck from California, although MSFC occasionally arranged to deliver the engines by boat.¹⁹

NASA'S "NAVAL FLEET" FOR THE SPACE PROGRAM

Marshall Space Flight Center began its first important waterborne work with the *Palaemon*, a converted Navy barge. The vessel was about 79 meters long, with two deck levels. The Navy used the Large



An S-II stage on its transporter.

Covered Lighter (YFNB) class during World War II, primarily during the Pacific campaigns, as floating supply and maintenance centers for forward operational areas. The vessels were originally designed to be self-contained. The lower decks were divided into crew quarters, galley, machine shop, and a machine room for a pair of diesel generators to supply power. The NASA conversion essentially retained the lower deck configuration, but the top deck was removed and covered over to house the Saturn I first stage as it rested on its transporter. The structure was "beefed up" at some points, and reinforcement strips on the floor helped carry the weight of the cargo. At the forward section, the *Palaemon* included a different berthing arrangement for a 10–12 man crew on the upper and lower deck levels, and included the radio shack and pilot house.

To propel the barges, MSFC's Project Logistics Office relied on commercial marine contractors like the Mechling Barge Lines, Incorporated, of Joliet, Illinois. One of Mechling's tugs, the *Bob Fuqua*, played an especially significant role in the Saturn program, beginning with the *Palaemon* and the shipment of the first of the Saturn I first stages from Huntsville to Cape Canaveral. Normally, river tugboats like the *Bob Fuqua* pushed, rather than pulled, a string of barges. With the tug in the rear, it was easier to maneuver the barges ahead and to drop off or pick up a barge at river docks. The high pilot house on the tug made it easy to see over the string of low, broad-beamed barges and follow the channel. The *Palaemon*, however, featured a high, metal-canopied superstructure for the protection of Saturn stages, reminiscent of a military quonset hut set atop the barge. Because the tug captain and pilot could not see to

STAGES TO SATURN

guide the barge, the *Palaemon*'s pilot house, not the tugboat's, became the bridge for controlling the barge and tugboat while under way, although the tug continued to supply power from the rear. In emergencies, control reverted back to the tug. This remote-control procedure, unique in barging operations, was ironed out in early 1961, based on water trials on the Tennessee River using the *Bob Fuqua* and the *Palaemon* with a test booster aboard. Barge captains and pilots had to relearn control techniques and maneuvers from the forward pilot house on the barge.

The *Bob Fuqua* possessed other advantages. It was also a seagoing tug, and the Mechling organization operated it under seaway rights that permitted the tugboat to move the *Palaemon* directly from port to port—from the Tennessee docks, down the Mississippi, across the Gulf, and up the Atlantic Coast to the launch site at Cape Canaveral. After leaving the Mississippi, the barge and tug followed the Gulf Intracoastal Waterway to St. George Sound, located off the Florida panhandle; across the Gulf of Mexico to San Carlos Bay (near Ft. Myers); through the Okeechobee Waterway across Florida to Stuart, on the Atlantic Coast; then up the Florida Intracoastal Waterway to the Cape Canaveral Barge Canal. The complete voyage from Huntsville covered about 3500 kilometers and took 10 days; by using the Intracoastal Waterway, the barge and its cargo traveled only 452 kilometers in open seas, and the route kept them no more than 80 kilometers from sheltered ports along the Gulf Coast. The barge and tug entourage usually included a 12-man complement: a five-man crew from Mechling to handle the barge and tug, a half-dozen NASA personnel traveling with the stage, and one government monitor with overall responsibility for the operations. The leisurely pace of the cruise, with the amenities of a well-equipped galley, showers, and air-conditioned quarters, often attracted upper-echelon MSFC personnel, if they could find a good excuse to go along.²⁰

The inaugural voyage of the *Palaemon* occurred in April 1961 when it departed from Huntsville for Cape Canaveral. Its cargo included a dummy S-IV stage for the SA-1 vehicle and a huge water-ballasted tank that simulated the size and weight of the Saturn S-1 first-stage booster. Crews at MSFC and the Cape rehearsed movements for loading, unloading, maneuvering the stage and its transporter, operating the barge. The *Palaemon* made the return trip in May, in time for its first operational cruise, carrying a dummy S-IV payload along with the first SA-1 flight stage that had just completed static-firing tests and final checkout at Huntsville. But on 2 June 1961, the single lock at Wheeler Dam on the Tennessee River collapsed. All river traffic halted and the *Palaemon* and its intended cargo were trapped upstream. The launch schedules were endangered, and NASA and MSFC scrambled to find a way to get the stage to Florida. The high national priority rating of the Saturn program and the cargo operations of the Atomic Energy Commission at Oak Ridge, Tennessee spurred prompt action. It did not take long for the

THE LOGISTICS TANGLE

TVA to build roads around the collapsed lock to a point below Muscle Shoals, Alabama. But the Saturn stage still needed a barge to carry it.

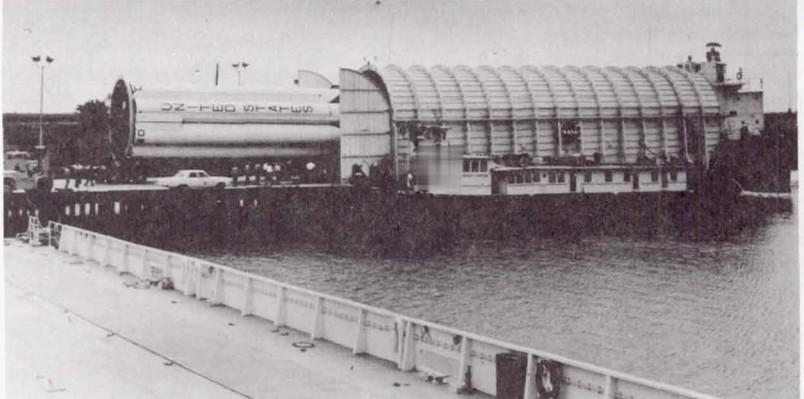
The Marshall center got in touch with the Navy, and requested another suitable YFNB barge. The Navy found one in the "mothball fleet" at Pensacola and MSFC personnel went to work on its modifications. It was appropriately christened *Compromise*. The cargo aboard the *Palaemon* finally left the MSFC docks on 5 August 1961; workers unloaded the cargo at Wheeler Dam and towed the Saturn SA-1 booster and S-IV dummy stage around the locks, reloaded the booster and dummy stage aboard the *Compromise*, and reached the Cape on 15 August, meeting the 10-day delivery schedule. NASA pressed a different tug into service, using a tow line, and the *Compromise* carried its load exposed; the tight schedule did not allow time to fit the barge with the distinctive metal canopy or controls of the *Palaemon*. Before the end of the year, *Compromise* was rebuilt to more suitable specifications, complete with protective canopy and a newly outfitted pilot house in front. Prior to the reopening of the Wheeler lock in the spring of 1962, NASA authorities decided that the original sobriquet for the *Compromise* did not convey the proper image. The barge was recommissioned the *Promise*.²¹

For transportation of the S-IV and S-IVB from the West Coast to Huntsville and then to the Cape, NASA at first relied on ocean freighters. The larger S-II stage needed more specialized treatment, since its size did not allow it to be stored within the confines of a freighter's hold or above deck. In December 1963, NASA concluded agreements with the Military Sea Transport Service to use the *Point Barrow* for shipment of S-II stages from California to test and launch sites in Mississippi and Florida. The *Point Barrow* was a Navy LSD (Landing Ship, Dock) that had seen extensive Arctic duty before its conversion for the space program. Beginning in 1964, the *Point Barrow* carried some S-IVB stages as well as the larger S-II under a protective canopy located in the rear of the ship.

The other large vessels that operated for the Saturn program included the U.S.N.S. *Taurus* and the YFNB barge *Poseidon*. The *Taurus*, similar to the *Point Barrow*, carried S-IVB and S-II stages to Mississippi test locations and to Kennedy Space Center, and the *Poseidon* was an oversized barge built to carry the big S-IC first-stage boosters of the Saturn V between MTF, MSFC, and Cape Kennedy. The open-deck barges *Little Lake* and *Pearl River* shuttled S-IC stages directly from the factory doors at Michoud to the test stands at MTF. The barges were left uncovered because the stages were hoisted directly off the barges into position at the vertical test stands. Because neither barge had a forward pilot house, the tugs that moved them featured a second bridge perched on a framework tower rising above the original pilot house on the tug. The rig looked like a seagoing forest fire watchtower to most spectators. The remainder of MSFC's fleet was on the West Coast for S-IV and S-IVB logistics. In addition, a small flotilla of seven tanker barges was

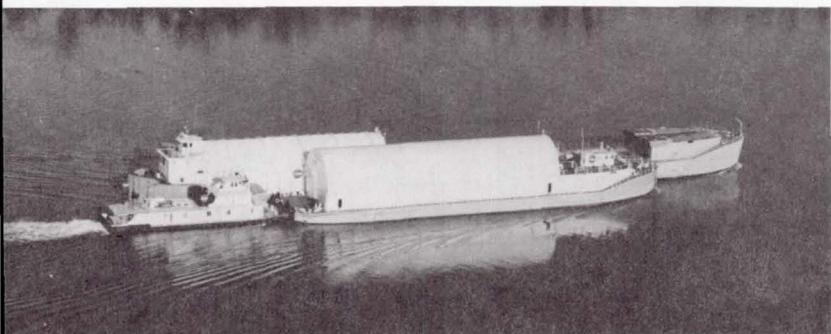
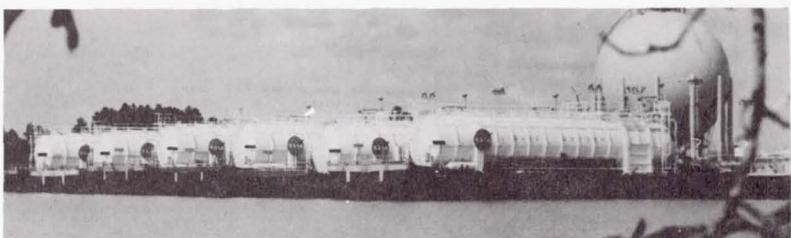
Saturn's Barges

An S-IB stage is loaded aboard the barge Palaemon at Michoud.



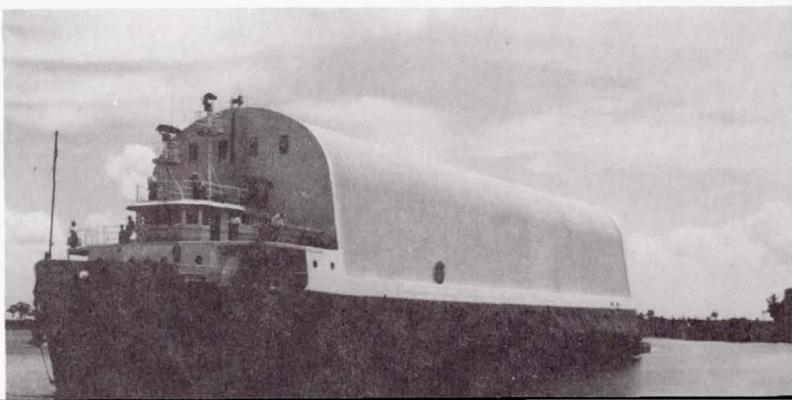
This fleet of six liquid-oxygen barges carried liquid oxygen from a nearby oxygen production plant to the Mississippi Test Facility. Three similar barges carried liquid hydrogen.

An S-IC stage is aboard the barge Pearl River at the Mississippi Test Facility. The high auxiliary bridge at the rear of the barge was constructed for use by the tug Apollo in seeing over the cumbersome bulk of the S-IC.



The barge Poseidon ferried S-IC and S-II stages between MSFC, Michoud, Mississippi Test Facility, and KSC.

This flotilla of three barges is being pushed up the Tennessee River early in 1965. The loaded ones carried first and second stages of the Saturn IB dynamic test vehicle.



THE LOGISTICS TANGLE

stationed at MTF. These barges were designed to carry a 875 000-liter tank of liquid hydrogen and moved between New Orleans and MTF to support the S-II and S-IVB static test firings.²²

William Mrazek, a top official in MSFC's Industrial Operations Division, once remarked that the Apollo program was possibly the greatest engineering program in history, overshadowing the Manhattan Project that produced the atomic bombs of World War II and outranking the efforts of the builders of the Egyptian pyramids.²³ He could have added that the Apollo project depended on the existence of other massive American enterprises in engineering such as the Panama Canal and the river navigation system managed by the Tennessee Valley Authority.

After tests at Sacramento, S-IVB stages were sometimes carried by barge and freighter either directly to the Atlantic Missile Range (by way of the Panama Canal and the Gulf of Mexico), or indirectly to MSFC—a 14-day voyage up the Mississippi, Ohio, and Tennessee rivers to Huntsville for testing, and back out again. Rifle fire raised a potential hazard for the Saturn rocket stages on the Mississippi and its tributaries. MSFC and contractor authorities began to worry that the huge targets on the barges might attract young boys and their small-bore rifles. Marshall asked for a Coast Guard escort for some of the first trips, not only as protection from adolescent sharpshooters, but also from riverbank moonshiners. John Goodrum, head of MSFC's logistics office, said that he didn't remember that a barge was ever hit, but somebody once put a bullet hole in the pilot house. "That's very common on the Mississippi," Goodrum laughed. The natives were pretty good shots, and no one ever got hurt—they just decided to let you know that they were there.²⁴

Full-sized stages for the Saturn I, Saturn IB, and Saturn V continued to move up and down the Mississippi and Tennessee rivers in the *Palaemon*, *Promise*, or *Poseidon*, aided by the specially rigged *Bob Fuqua*. Occasionally, some of the components of one of the stages had to be carried back and forth between Michoud and Huntsville for additional tests and analysis at MSFC, and these components could be lashed down as a deck load on one of the regular commercial barges that plied the rivers. Components for the S-IC stage took the water route to MSFC for testing; one cargo consisted of the 10-meter diameter intertank assembly at 6650 kilograms and 2 "Y ring" supports, 10 meters in diameter and over 6800 kilograms apiece. The average voyage of 1996 kilometers from New Orleans docks to the MSFC docks in Huntsville involved several segments and changeovers as the barge string was passed from one towboat to another. The first segment ran 1396 kilometers upriver to Cairo, Illinois, and took 10 days. At Cairo, the "rocket barge" joined a barge group under the control of an Ohio River towboat for the 76-kilometer leg to Paducah, Kentucky, the outlet of the Tennessee

STAGES TO SATURN

River. The Igert Towing Company's *Bill Dyer* acquired control of the barge at Paducah and began the 521-kilometer run to Huntsville.

On the Tennessee River, the massive, federally supported Apollo-Saturn project took advantage of a predecessor: the Tennessee Valley Authority project. Nine multipurpose locks and dams created a navigation channel from Paducah to Knoxville, Tennessee, a span of 1014 kilometers. At an average depth of 3 meters, the river channel was quite comfortable for river barge operations. For the *Bill Dyer*, the first lock to lift the towboat and barge occurred just 35 kilometers from Paducah. Then followed a placid, 322-kilometer cruise at about 14 kilometers per hour as the river turned south across the western end of Tennessee, past a series of small river landings with whimsical names like Sarah's Garter and Petticoat Riffle. At Pickwick Dam, near the border of Alabama, the barge group was lifted again and turned east toward Huntsville. En route were additional locks at Wilson Dam and Wheeler Dam, elevating the *Bill Dyer* and its cargo a total of 77 meters within 407 kilometers of river channel. About 8 hours after emerging from the Wheeler locks the *Bill Dyer* put in at the MSFC boat slip, and the 521-kilometer journey on the Tennessee was completed.²⁵

SPACECRAFT BY AIRCRAFT: NASA'S AIR CARGO SERVICE

Helicopters were occasionally pressed into service to meet logistical needs for the Apollo-Saturn program. In support of vehicle dynamic tests at Huntsville, an Army CH-47A, dangling its cargo underneath, flew from Tulsa, Oklahoma, to Huntsville. The Saturn IB load consisted of an adapter unit that connected the instrument unit to the service module and housed the lunar module. The tapered adapter component, 9 meters long and 6.7 meters in diameter at the base, made quite an impression as it swayed through the air during the 965-kilometer flight from North American's facility at Tulsa.²⁶ The most impressive aerial deliveries were made by special transport aircraft that were designed to carry entire Saturn S-IV and S-IVB upper stages.

As the Saturn I program progressed, NASA officials became increasingly concerned about coordinating arrival of separate stages at the Cape to meet the launch schedules. Lower stages for the Saturn I and Saturn IB required a comparatively short voyage from Huntsville and from Michoud. Delivery of the S-IV and S-IVB from California also involved the use of seagoing barges and transports to carry these upper stages down the Pacific Coast, through the Panama Canal, across the Gulf of Mexico, and finally across Florida to Cape Canaveral. The odyssey of the S-IV and IVB stages required occasional side trips up the Mississippi and Tennessee rivers to Huntsville for additional tests at MSFC facilities before returning to the Cape. This complex and slow operation and the

THE LOGISTICS TANGLE

potential delays from foul weather at sea generated increasing concern about meeting carefully coordinated deliveries of vehicle stages and related hardware. Transportation of the larger S-II second stage of the Saturn V and the S-IVB third stage from California to the Cape multiplied the concern. Another potential weak link was the Panama Canal. If the canal were to be shut down for some reason, seaborne shipments would be forced around South America and the carefully calculated launch schedules would collapse.²⁷

Against this background, managers within NASA began thinking about other modes of transportation to ensure rapid delivery of upper Saturn stages, beginning with the S-IV. The size of the S-IV ruled out delivery to the Cape by rail or road. As the lead center of launch vehicle development, MSFC let a contract in 1960 to the Douglas Aircraft Corporation to determine the feasibility of air transport. A Douglas assessment team spent several months on the project and came up with a proposal that envisioned a "piggyback" concept that used an Air Force C-133 transport. Design studies included pictures of the rocket stage positioned above the C-133 and perched atop streamlined fairings. Because the stage was exposed to the passing airstream, planners expected to fit the stage with a streamlined nose cone, with vertical stabilizers at the rear to enhance its aerodynamic qualities in transit. Suggestions from other sources ran the gamut from airplanes to gliders to lighter-than-air vehicles. One proposal envisioned the use of a blimp, which would putter along from California to Florida with a swaying S-IV stage slung underneath. As late as 1963 serious thought was given to resurrecting a modern successor to the prewar dirigible, with an interior cargo hold to carry rocket stages.²⁸

The Douglas organization already possessed its own reservoir of experience in the transportation of rockets by aircraft. The Douglas Thor IRBM had been freighted regularly on transcontinental and intercontinental flights by Douglas C-124 Globemasters, and the company was confident that this mode of transport was practical because its own aerial operations had not damaged any rocket or its systems. The Thor, however, had been designed for airborne shipment,²⁹ and the situation was now reversed. Douglas was ready to listen when approached with an unusual scheme: the modification of an existing aircraft to completely enclose the rocket stage with an airplane's fuselage.

The idea of a bloated cargo airplane originated with an imaginative group associated with John M. Conroy, aerial entrepreneur of an outfit aptly named Aero Spacelines, Incorporated, in Van Nuys, California. Aero Spacelines intended to acquire surplus Boeing B-377 Stratocruisers. About 1960, Conroy and some partners acquired title to over a dozen four-engined airliners, used mainly by Pan Am and Northwest Orient on their intercontinental routes during the Stratocruiser's heyday in the 1950s. The Conroy group at first planned to use the planes for

STAGES TO SATURN

nonscheduled air carry operations, but airlift for Air Force rockets also looked promising. By 1961, plans had progressed to fly NASA's new family of large launch vehicles.³⁰

Drawing heavily on his own financial resources, Conroy pushed the idea of his bulbous, "volumetric" airplane despite the considered opinion of many aircraft engineers and aerodynamicists that no plane could be distorted and distended enough to swallow an S-IV rocket stage and still be able to fly. But Conroy was persuasive. R. W. Prentice, who managed the S-IV logistics program at Douglas, remembered him as real "swash-buckler," the sort of aviation character that reminded him of the cartoon hero named "Smilin' Jack." Conroy apparently found some kindred souls among influential Douglas executives, because he persuaded the company to go along with him on a presentation to NASA and MSFC. Some of the NASA managers were unconvinced, but the energetic Conroy touched a responsive chord in MSFC's visionary director, Dr. Wernher von Braun. As John Goodrum, chief of MSFC's logistics office, recalled the sequence of events, von Braun warmed to the idea from the start. The idea was innovative and its boldness appealed to him. Neither MSFC nor NASA Headquarters could allocate substantial funds to such a project at the time. Nevertheless, buoyed by the interest evinced at both Douglas and MSFC, Conroy decided to plunge ahead, although there was no guarantee of a contract.³¹

The first phase of the project called for lengthening the fuselage (by inserting the cabin section of another Stratocruiser) to accommodate the S-IV stage. After the flight test of that modification, phase two called for the enlargement of the plane's cabin section to approximately double its normal volume. The swollen, humpbacked addition to the original Boeing airframe was originally fabricated as a nonstructural element stuck on the top of the fuselage. This alteration allowed test pilots and engineers to conduct flight tests and analyze the altered flying characteristics in comparative safety. The first flight occurred on 19 September 1962, followed by more than 50 hours of cross-country trials and other experimental flights. Satisfied that the reconfigured aircraft could indeed fly, workmen finally cut away the original inner fuselage and the massive external shell was mated to the basic airframe as a load-bearing structure. The name Aero Spacelines selected for its unique plane was a natural. The former Stratocruiser became a B-377 PG: the Pregnant Guppy. The new plane had cost over \$1 000 000.³²

The Guppy's designers intended to make the plane a self-contained cargo transportation system. The fuselage separated just aft of the wing's trailing edge to load and unload the S-IV and other cargoes. The ground crew unloaded and attached three portable dollies to the rear part of the plane and disengaged the various lines, cables, and bolts connecting the fuselage sections. The rear portion was then rolled back to expose the plane's cavernous hold.³³

THE LOGISTICS TANGLE

In the course of work on the Guppy, Conroy began running out of cash and credit. He figured he needed some tangible support from NASA in the form of an endorsement to keep his creditors at arm's length. On 20 September 1962, only one day after the first air trials of the reconfigured prototype cargo version, Conroy and an adventuresome flight crew took off for a demonstration tour. At this stage of the plane's development, the B-377's original fuselage was still intact, and the massive hump attached to the outside was held up by an interior framework of metal stringers and wooden two-by-fours. Conroy had to get a special clearance from the Federal Aviation Administration which allowed him to proceed eastward from Van Nuys, as long as he avoided major population areas en route. Following several interim stops, the Pregnant Guppy flew to Huntsville, where Conroy wanted to demonstrate the plane to MSFC officials and perhaps get some form of unofficial encouragement to enable him to continue the plane's development.

He landed at the airstrip of the Army's Redstone Arsenal, a facility shared jointly by MSFC and the Army. The Guppy was visited by a mixed group of scoffers and enthusiasts, including von Braun. While some onlookers made sour jokes about the reputed ability of the awkward-looking plane to fly Saturn rocket stages from the Pacific to the Atlantic coast, von Braun was delighted. With both time and money in short supply, Conroy wanted to pull off a convincing test of the Guppy's ability to fly a heavy load. Because there was no time to install enough sandbags in the hold to simulate the proposed cargo capacity, the plane was completely gassed up with a load of aviation fuel to make up the weight difference. MSFC's logistics chief, John Goodrum, observed the proceedings, and most of the people around him seemed very doubtful of the plane's potential. "In fact," remembered Goodrum, "there were some pretty high ranking people who stood right there and shook their heads and said it just wouldn't fly—there is no way!"

With Conroy at the controls, the big plane lumbered down the runway and into the air. The pair of MSFC observers aboard this first flight included Julian Hamilton, a key manager in Saturn logistics programs, and Herman Kroeger, a member of the von Braun group since the V-2 program in Germany and a former test pilot. Even with the number one and two engines out, the plane could maintain course and altitude with only light control. This feat so impressed ex-test pilot Kroeger that he lapsed into German in describing it to his colleagues after the plane landed. Von Braun was so interested that he wanted to fly in the airplane. The MSFC director crawled in the airplane and took off, to the consternation of those still dubious about the airworthiness of the fuel-heavy airplane braced on the inside by a wooden framework. The flight was uneventful, and informal contract talks began the same day. There was little doubt that Conroy needed some firm support. His

STAGES TO SATURN

finances were in such bad shape that he reached Huntsville only by borrowing some aviation gas from a friend in Oklahoma, and MSFC agreed to supply him with enough gas to fly home to California.³⁴

Conroy was able to supply information for more serious contract negotiations by late fall of 1962. Conroy reported in a letter to von Braun that performance of the Pregnant Guppy guaranteed cruising speed in excess of 378 kilometers per hour. The correspondence also revealed the growing extent of MSFC cooperation and support for the proposed Guppy operations involving cooperation from military bases, although no official contracts had been signed. Aero Spacelines planned to keep critical spares at strategic locations along its route structure to reduce downtime in case of malfunctions. This arrangement included the special allocation of a "quick-engine-change" unit at Patrick AFB, Florida, near the launching sites of Cape Canaveral. NASA also planned to arrange for Aero Spacelines to purchase supplies of fuel and oil at the military bases along the Guppy's route.³⁵

In the spring of 1963, the space agency was planning the first two-stage launch of the Saturn I vehicle, designated SA-5. The first four launches had carried inert second stages, and SA-5 had special significance as the first of the giant Saturn boosters to have both stages "live" and operational. The agency was growing anxious over the delivery of the S-IV-5 stage because of a time slippage caused by test problems, and the Pregnant Guppy would save considerable time by flying the stage from California to the Cape in 18 hours, as opposed to 18–21 days via ship. In a letter dated 25 April 1963, NASA's Director of Manned Space Flight, D. Brainerd Holmes, emphasized the Guppy's importance to Associate Administrator Robert Seamans. Holmes wanted to make sure that the FAA was "advised of NASA's vital interest" in securing the Pregnant Guppy's prompt certification so that lost time could be made up in the delivery of the S-IV-5 stage. Holmes pointed out that NASA had also made several telephone calls to FAA officials.³⁶

As evidence of NASA's growing commitment to Guppy operations, Aero Spacelines was finally awarded a contract from MSFC, to cover the period from 28 May–31 July 1963, to complete the plane's tests and make an evaluation as soon as possible. The FAA awarded the B-377 PG an airworthiness certificate on 10 July, and MSFC immediately conducted a transcontinental trial flight with a simulated S-IV stage aboard. Although the Pregnant Guppy did not receive its final certification as a transport craft until 13 November 1963, NASA relied on the plane to carry Apollo spacecraft hardware to Houston during the late summer months, and in mid-September the Pregnant Guppy took on the S-IV-5 stage at Sacramento for delivery to Cape Kennedy for the launch of SA-5. Technical problems in the first stage delayed the launch for many weeks, but the two-stage rocket finally made a successful flight on 29 January 1964.³⁷

THE LOGISTICS TANGLE

The Guppy saved up to three weeks in transit time and effected substantial savings in transportation costs, and won endorsements and long-term contracts from NASA officials. The plane was operated by MSFC but carried a variety of NASA freight including launch vehicles for the Gemini program, Apollo command and service modules, hardware for the Pegasus meteoroid detection satellite, F-1 engines, the instrument unit for Saturn I, and "other general outsized NASA cargo."³⁸

For these reasons, as well as NASA's concern for the larger space hardware in the Saturn IB and V programs, NASA managers expressed interest in correspondingly larger aircraft. Because the S-IVB stage was larger than the S-IV, it would require a larger plane if air operations were to be continued. A larger plane could carry the instrument unit for both the Saturn IB and the Saturn V as well as the Apollo lunar module adapter unit. Moreover, a second plane could serve as a backup for the original Guppy. At one point in the discussions about a second-generation aircraft, serious consideration was given to the conversion of an air transport large enough to handle the S-II second stage of the Saturn V.

Even before the Pregnant Guppy had won its first NASA contract, Conroy was writing to von Braun about a successor aircraft equipped with powerful turboprop engines and large enough to transport the S-IVB. NASA did not seriously consider the second-generation Guppy until the original Pregnant Guppy had demonstrated its worth. Robert Freitag, NASA Headquarters' Director, Manned Space Flight Center Development, wrote von Braun in early 1964 noting the "outstanding success we have enjoyed with the Pregnant Guppy." In addition to the Pregnant Guppy's use by MSFC to carry rocket stages, Freitag said the Manned Spacecraft Center in Houston was anxious about having a backup aircraft available. Freitag envisioned three possibilities: acquire a similar Pregnant Guppy and rely on water transport for the S-IVB and S-II stages, acquire a larger type for S-IVB operations and leave the S-II to water transport, and acquire an S-II-size aircraft that could also handle the smaller S-IVB. Any of the three possibilities could meet the logistical requirements of the Houston center, but a decision was needed soon; the timing for production and delivery of Saturn rocket stages to the Cape to meet launch schedules was in question. "Since time is of the essence," Freitag concluded, "I would appreciate receiving your recommendations including advantages and technical funding plan for accomplishing our objectives at the earliest possible date."³⁹

Evidence suggests that MSFC gave serious thought to a mammoth aircraft capable of handling a rocket stage the size of the S-II. On 2 February 1964, MSFC drafted a request for quotation titled "Large Booster Carrier Aircraft." The document suggested the development of either an airplane or a lighter-than-air vehicle capable of transporting the

STAGES TO SATURN

S-II (or S-IVB) to test sites in southern Mississippi and the Cape. "In any case, the program is to be characterized by austere funding and early delivery schedules." Several companies proposed various schemes, including the use of modified B-36 bombers or English-built Saunders-Roe Princess flying boats.⁴⁰ None of these plans ever materialized. NASA concluded that an S-II cargo aircraft would take too long to develop and would cost too much. Also the number of planned Saturn V launches was revised downward, reducing the requirements for S-II transportation. The S-IVB, however, was programmed for frequent launches in both the Saturn IB and Saturn V class of vehicles, so the desire for a backup airplane persisted.⁴¹ With its Boeing Stratocruiser inventory, Aero Spacelines proved to be ahead of any competition in supplying a second volumetric air transport.

As before, Aero Spacelines developed the new aircraft with its own resources, although personnel from MSFC came to California to cooperate on the design studies, and a flight-test expert from NASA's Flight Research Center at Edwards, California, worked very closely with the design team. Originally dubbed the B-377 (VPG) for "Very Pregnant Guppy," the second-generation plane finally emerged as the "Super Guppy," or B-377 SG. The larger, heavier cargoes for the Super Guppy required increased horsepower. Although parts of three other B-377 aircraft were incorporated into the Super Guppy, the cockpit, forward fuselage and wing sections, and the engines came from a Boeing C-97J, an Air Force transport version of the commercial Stratocruiser. This aircraft had Pratt & Whitney turboprop engines. Conroy realized that it was imperative for his big new airplane to have the more efficient and powerful turboprop powerplants. Conroy had learned from his contacts in the Air Force that the C-97J airplanes were headed for retirement, and he had hoped to get the airframes as salvage and the engines on a low-priced lease. Conroy succeeded, with NASA lending special assistance in securing the engines. During the spring of 1965, NASA's Office of the Administrator made overtures to the Air Force: "We definitely feel that it would be in the public interest and advantageous to the government if these engines were made available" to transport rocket stages, engines, and other large cargoes. "Under these circumstances," NASA explained, "we would appreciate it if you would approve the proposed lease."⁴² Conroy got his engines, and the Super Guppy began acceptance tests before the year was out.

NASA wanted to put the aircraft in service early in 1966, after the plane had proved its flying capabilities, although final FAA certification came later in the spring. John C. Goodrum, chief of MSFC's Project Logistics Office, felt that the utility of the Super Guppy was of such importance that it should be considered operational for "critical cargoes" on a "limited basis" as soon as possible. Although FAA examiners had not yet flown the Super Guppy by March, Goodrum urged operational

THE LOGISTICS TANGLE

service based on the judgment of NASA's own test pilots at Edwards that the plane was satisfactory for transport duties. He advised NASA Headquarters that MSFC planned "immediate utilization" of the airplane to ship a Saturn instrument unit manufactured by IBM in Huntsville. The Super Guppy landed at Huntsville within a week, apparently by special arrangement with the FAA, and flew the IU to the Douglas plant at Huntington Beach for systems testing with an S-IVB stage. The plane made a return trip before the end of the month and delivered another S-IVB test stage to MSFC.⁴³

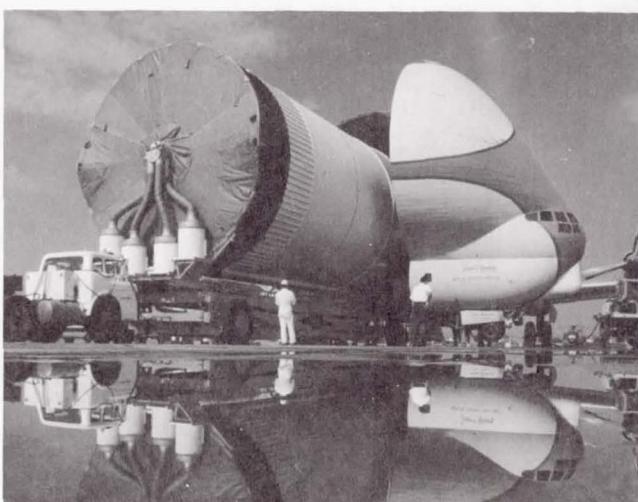
As the Super Guppy became fully operational during 1966, its success reflected the expertise accumulated in missions using its predecessor. The Super Guppy's cargo was loaded from the front, and the entire forward section of the fuselage was built to swing aside on hinges just ahead of the wing's leading edge. This modification added to the ease and swiftness of its operations, and was largely dependent on the ground support techniques and equipment developed for the Pregnant Guppy in the early 1960s. After modification, equipment designed for the S-IV served equally well for the larger S-IVB. The cargo lift trailer (CLT) became a major item in the support equipment developed for handling space hardware as air cargo. The CLT was developed at MSFC and operated on the scissor-lift principle to raise its load for transfer into the cargo hold of the airplane. The CLT could also be used as a transporter over short distances. A movable pallet supported the S-IV on the CLT. The pallet had cradle supports fore and aft that were linked to the pallet with shock mounts of an oil-spring type. The CLT raised the pallet to the loading level of the cargo bay, then the pallet was rolled off and secured inside the aircraft. For aerial shipment, ground crews did not use the shroud that protected the rocket stage during water transport. Instead, engineers designed lightweight covers to fit over the exposed areas fore and aft, and a bank of static desiccators in the propellant tanks comprised the environmental control system while airborne. Both Guppy aircraft carried the instrumentation to monitor pressure, humidity, temperature, and vibration readings in flight as part of the plane's permanent equipment. In a typical delivery sequence, the rocket stage moved eight kilometers overland from the Douglas plant at Huntington Beach to the Los Alamitos Naval Air Station. After loading the stage, the pilots flew north to Mather Air Base, not far from SACTO. When stage tests were completed, the final leg of the airborne logistics sequence concluded with delivery at Cape Kennedy for preflight check-out and launch.⁴⁴

Although no stage damage occurred during the aerial delivery by the Guppies, the planes occasionally experienced some troubles, and some delivery schedules were affected by adverse weather. The Guppies might make three or four stops between California and Florida, depending on the winds aloft and weather en route. Aero Spacelines relied on a



Saturn Air Transport

Top left, an Army CH-47A helicopter arrives at the MSFC dynamic test stand with the Saturn IB adapter unit it has flown 970 kilometers from Tulsa, Oklahoma. Top right, the Pregnant Guppy aircraft is loading an S-IV stage into its aft fuselage. Above, the Super Guppy arrives at MSFC in fall 1966. Right, the Super Guppy takes on an S-IVB stage.



THE LOGISTICS TANGLE

string of selected SAC bases and other Air Force fields for fuel and operational support, and these installations were normally alerted ahead of time for the appearance of the strange-looking Guppy in the landing pattern. Not long after the start of Pregnant Guppy flights, a misadventure occurred, and NASA's S-IV rocket stage was temporarily impounded by Air Force security personnel. Don Stewart, who represented MSFC as a monitor for the early operational flights, recalled that the Guppy pilot had been forced off his normal route out of Los Angeles to avoid bad weather, and the plane had begun to run low on gas. Both Stewart and the pilot thought their alternate field, a SAC base, had been notified of Guppy operations. They were mistaken. After a night landing, the plane was surrounded by SAC security police brandishing carbines and M-1 rifles. The SAC guardsmen were caught off balance by the large and unusual aircraft that carried a rocket, and they directed the plane to a remote corner of the airfield until the intruder's credentials could be verified. The Guppy crew dozed fitfully in the plane until the base commander was convinced of Stewart's story, checked with the proper authorities, and finally issued a clearance to refuel and take off in the early hours of the morning.⁴⁵

In flight, the Pregnant Guppy behaved normally, although Air Force and NASA ground crews had to learn to cope with some of its unusual idiosyncracies on the ground. During a stop at Ellington Air Force Base at Houston, high winds swept into the vast hold of the detached aft section, and caused light damage to the plane's tail. After a couple of mishaps involving the Super Guppy, designers beefed up the massive dome and redesigned the latching mechanisms on the hinged nose section. The Super Guppy experienced occasional engine problems, and NASA wisely kept the plane on the ground during high winds.⁴⁶

Despite these occasional incidents, the ungainly looking airplanes routinely performed their duties week after week, and flew one-of-a-kind, multimillion dollar cargoes between NASA facilities, contractor plants, and the launch site at Cape Kennedy. The Guppies transported other diversified cargoes in addition to rocket stages and engines. During 1968, the Super Guppy carried the special environmental chamber used for final preparation of the manned Apollo command module prior to launch, as well as carrying cryogenic tanks for an experimental nuclear rocket. As the Skylab orbital workshop progressed in the late 1960s and early 1970s, the Guppies ferried such components as the multiple docking adapter, the Apollo telescope mount, and the Skylab workshop itself (adapted from the S-IVB).⁴⁷ The success of Aero Spacelines and its original Pregnant Guppy attracted the attention of other firms with thoughts of diversification, and in July 1965 the company was acquired by the Unexcelled Chemical Corporation. The new organization not only proceeded with the Super Guppy configuration; it also constructed a

STAGES TO SATURN

small fleet of volumetric aircraft to haul outsized cargoes such as large aircraft sections, jet engines, helicopters, oil drilling equipment, and boats for NASA as well as for the Air Force and commercial firms.⁴⁸

Although the cargoes carried by the Guppies were limited in number, they were unique and of considerable importance. In the opinion of John Goodrum, head of MSFC logistics, the payoff of the Guppy operations was exceptional for NASA, especially during the 1966–1967 period, when closely scheduled Saturn IB and Saturn V launches put a high premium on rapid aerial deliveries of S-IVB stages and instrument unit components to Cape Kennedy. It would be too strong to say that the Guppy operations saved the Saturn program, Goodrum said reflectively, but without the availability of the unique planes, NASA might have been forced to scrub some of the scheduled launches and might have incurred horrendous costs in money and time.⁴⁹

The Guppy shipments of outsize components such as jet engines and wing sections offered a unique and highly valuable mode of transport in terms of commercial operations. The Guppies carried a limited number of otherwise awkward and critical items in situations where the saving of time was paramount. Nowhere was this capability more evident than in the nation's Apollo-Saturn program.

SUMMARY

Logistics were not thoroughly analyzed at the start of the Apollo-Saturn program. The logistical requirements of Saturn parts, spares, and propellants, including the delivery of large rocket stages from the West Coast to the East Coast, took considerable manpower and unanticipated planning time. The dimensions of the stages required custom-built transporters, customized inspection equipment, and other accessories. Logistics managers learned to allot plenty of time for the planning and coordination that was necessary to move Saturn rocket stages over public roadways.

The extent of NASA's water and air operations was little known to the general public. The water routes encompassed passage through both the Pacific and the Atlantic oceans, and required negotiation of the Panama Canal, the Gulf of Mexico, and the Intracoastal Waterway. The waterborne routes were time-consuming, but remained the only feasible mode of transporting the largest of the Saturn stages. Saturn transportation also relied on inland waters for transportation between the Gulf Coast and Huntsville; logistics managers took advantage of canals and other waterways for the transfer of the S-IC and S-II stages from the manufacturing center at Michoud and from test areas at the Mississippi Test Facility. The airborne operations represented the imagination and ingenuity of the Saturn program. The Guppy aircraft made an invaluable contribution to the success of the program.



The Navy assisted NASA with water transportation of Saturn stages. It made available the U.S.N.S. Point Barrow, which first carried S-IVB stages from California through the Panama Canal to the Gulf coast; when the Guppy aircraft took over S-IV transport, Point Barrow carried S-II stages from California to the Mississippi Test Facility.

SATURN TRANSPORTATION EQUIPMENT

ITEM	DESCRIPTION	USE	OWNER OPER.	OPER. COST*	REMARKS
USNS POINT BARROW	MODIFIED NAVY AKD COVERED	TRANSPORTS S-II STAGES TO MICHoud AND S-IB, S-IC & SIVB TO KSC	US NAVY MSTS	\$4500 DAY	
BARGE ORION	MODIFIED NAVY YFNB COVERED	RIVER & OCEAN TRANSPORT OF S-IC & S-II STAGES; PRIMARILY BETWEEN MICHoud, MSFC AND KSC	NASA MSFC	\$3000 DAY	
BARGE PROMISE	MODIFIED NAVY YFNB COVERED	TRANSPORT OF S-IB STAGES BETWEEN MICHoud, MSFC, AND KSC	NASA MSTS	\$3000 DAY	MICHoud
BARGE PALAEMON	COVERED BARGE	TRANSPORT OF S-IB STAGES BETWEEN MICHoud, MSFC, AND KSC	NASA MSFC	\$3000 DAY	MICHoud
POSEIDON	MODIFIED NAVY YFNB COVERED	RIVER & OCEAN TRANSPORT OF S-IC & S-II STAGES; PRIMARILY BETWEEN MICHoud, MSFC AND KSC	NASA MSFC	\$3000 DAY	MICHoud
BARGE PEARL RIVER	MODIFIED NAVY YFNB UNCOVERED	TRANSPORTS S-IC & S-II STAGES BETWEEN MICHoud AND MTF	NASA MSFC	\$2200 DAY	MICHoud/MTF REMOTE CONTROL
BARGE LITTLE LAKE	MODIFIED NAVY YFNB UNCOVERED	TRANSPORTS S-IC & S-II STAGES BETWEEN MICHoud AND MTF	NASA MSFC	\$2200 DAY	MICHoud/MTF
SUPER GUPPY AIRCRAFT	MODIFIED BOEING YC97J AIRCRAFT	TRANSPORTS S-IVB STAGES, INSTRUMENT UNITS, LEM ADAPTERS AND F-1 ENGINES	AERO SPACE AERO SPACE	\$16.00 MILE	TRANSPORT CARGO FOR DOD, MSC, & MSFC
PREGNANT GUPPY AIRCRAFT	MODIFIED BOEING 377 AIRCRAFT	TRANSPORTS APOLLO S/C, & S/C COMPONENTS	AERO SPACE AERO SPACE	\$16.00 MILE	TRANSPORT CARGO FOR DOD, MSC, & MSFC

*COSTS SHOWN ARE FOR FULL CREW IN OPERATIONAL STATUS

ble contribution to the maintenance of schedules, which held the line on costs.

NASA and MSFC implementation of a logistics plan was an essential factor in meeting deadlines, especially for rocket launches. Stages reached Kennedy Space Center on schedule, and NASA's program for a lunar landing before the 1970s stayed close to its timetable.

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VI

Step by Step

Few events are as spectacular as that of a Saturn V at liftoff en route to the moon. In fact, the commanding role of the mammoth vehicle has tended to obscure its supporting players, the Saturn I and Saturn IB boosters. Chapter 11 recapitulates some of the milestones of these earlier rockets and describes some of the payloads and visual instrumentation used in early launches to acquire crucial information about the near-Earth environment and the behavior of exotic propellants in the weightlessness of space.

Perhaps the biggest gamble of the Apollo-Saturn program rode on the launch of AS-501, the first Saturn V to lift off from Cape Kennedy. The decision to go "all up" on this launch circumvented the costly and time-consuming process of incremental flight testing of each stage prior to launching a complete vehicle. This mission, followed by troubleshooting the problems of AS-502, the first manned Saturn V launch (AS-503), and the first lunar landing mission (AS-506, or Apollo 11), constitute the highlights of chapter 12.

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III

Qualifying the Cluster Concept

The Saturn I flight tests were uniformly successful, and the unique size and complexity of the clustered rocket made its success all the more remarkable. Midway in the Saturn I flight test programs, Dr. F. A. Speer, Chief of MSFC's Flight Evaluation and Operational Studies Division, Aero-Astrodynamic Laboratory, summarized the first five flights (which included the first live two-stage vehicle, SA-5); a summation that turned out to be a prognosis for all 10 vehicles of the Saturn I series. "All five flights were complete successes," Speer reported, "both in achieving all major test missions and in obtaining an unprecedented volume of system performance data for flight analysis." Speer asserted, "It is correct to state that, up to this point, no major unexpected design change had to be initiated on the basis of flight test—thus proving the design maturity of the Saturn I vehicle."¹ Troubles occurred, to be sure; but they did not cause serious delays in the mission schedules, nor serious redesign efforts.

On 27 October 1961, the first Saturn lifted from the launch pad at Cape Canaveral. All the static tests, dynamic tests, and test firings before this first launch had pointed to a successful mission, but until the liftoff of SA-1, no one could say for certain that an eight-engine monster like the Saturn would really work. The long countdown demonstrated the compatibility of the ground support equipment, and the launch crew released the "bird" (as NASA crews called the rockets) with no technical "hold" to mar the mission. The SA-1 vehicle soared to an altitude of 137 kilometers and impacted the Atlantic Ocean 344 kilometers downrange.

STAGES TO SATURN

The postmission report verified the confidence of the Marshall team in the structural rigidity of Saturn's airframe, and the quartet of gimbaled outboard engines demonstrated the design goals of vehicle control and reliability. The validity of the concept of the clustered Saturn booster could no longer be questioned.²

EARLY BIRDS: BLOCK I AND BLOCK II

The 10 launches of the Saturn I booster included both Block I and Block II versions. The H-1 engine was common to all the vehicles, but a number of significant differences distinguished Block I from Block II. The most visible distinguishing feature for the Block I series, SA-1 through SA-4, was the absence of aerodynamic fins on the first stage. Moreover, the Block I vehicles did not include live upper stages. Consistent with NASA's building block concept and the requirements for validating the clustered concept first, these first Saturn I launches used live lower stages only. The dummy upper stages looked like the future live versions, had the same approximate center of gravity, and had identical weight. Inert S-IV and S-V stages, topped by a nose cone from an Army Jupiter rocket, brought the typical height of the Block I series to about 50 meters.

The flight of SA-1 was remarkable for the small number of modifications that were required for succeeding flights. Experience gained from successive launches inevitably resulted in changes, but the only major difficulty that turned up with SA-1 was an unanticipated degree of sloshing of propellants in the vehicle's tanks. Beginning with vehicle SA-3, additional antislosh baffles were installed, which brought this undesirable characteristic under control. None of the Block I missions called for separation of the upper stages after the S-1 first-stage engine cutoff, although the SA-3 and SA-4 vehicles experimentally fired four solid-fuel retrorockets, anticipating the separation sequence of Block II missions. Other preliminary test items on SA-4 included simulated camera pods and simulated ullage rockets on the inert S-IV stage. The last two vehicles also carried a heavier and more active load of electronics and telemetry equipment. The telemetry equipment and associated test programs varied with the goals of each mission, but the total array of such gadgetry and the means of acquiring information help explain not only the success of the Saturn program but also the comparatively low number of R&D flights required to qualify the vehicle as operational.

The flight of SA-4 culminated with only seven engines firing instead of eight. One of the appealing features of clustered engines involved the "engine-out capability"—the prospect that, if one engine quit, the remaining engines could compensate by burning longer than planned. So NASA technicians programmed a premature cutoff of one engine 100 seconds

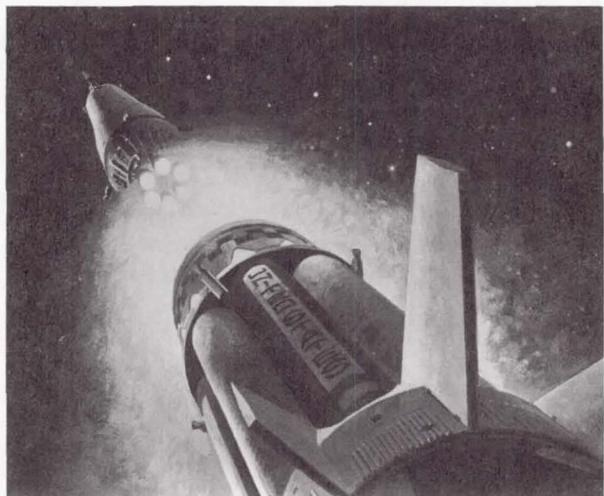
QUALIFYING THE CLUSTER CONCEPT

into the flight. The experiment succeeded, the SA-4 performing as hoped on the remaining seven engines.

During this basically uneventful series of launches, the Saturn I carried its first payloads. The missions of SA-2 and SA-3 included one very unusual experiment, called Project Highwater, authorized by NASA's Office of Space Sciences. The inert S-IV and S-V stages for these launches carried 109 000 liters (30 000 gallons) of ballast water for release in the upper atmosphere. As NASA literature stated, "release of this vast quantity of water in a near-space environment marked the first purely scientific large-scale experiment concerned with space environments that was ever conducted." One of the questions apparently bothering NASA planners was the consequences of a stage explosion in space or the necessity of destroying one of the Saturn rockets at a high altitude. What would happen to the clouds of liquid propellants released in the upper atmosphere? Would there be radio transmission difficulties? What would it do to local weather conditions? Project Highwater gave answers to these questions. At an altitude of 105 kilometers, explosive devices ruptured the S-IV and S-V tanks, and in just five seconds, ground observers saw the formation of a huge ice cloud estimated to be several kilometers in diameter, swirling above the spent stage to a height of 145 kilometers above the sea. It was a dramatic sight for the observers below at Cape Kennedy and marked the first use of the Saturn launch vehicles for a purely scientific mission.³

During 1964, introduction of the Saturn I Block II vehicles marked a new milestone in large launch vehicle development. To the casual observer, the most obvious distinction was the addition of the eight aerodynamic fins to the lower stage for enhanced stability in flight. As far as NASA was concerned, the most significant feature of Block II was the addition of a live upper stage, the S-IV, built by Douglas. Moreover, the S-IV stage also marked the inauguration of liquid hydrogen propellant technology in the Saturn vehicle program; six RL-10 liquid hydrogen rocket engines supplied by Pratt & Whitney were used. These engines in the upper stage would allow orbital operations for the first time in Saturn I launches. Above the S-IV stage, the Block II vehicles also carried the first instrument canisters for guidance and control. The instrument canister controlled the powered ascent of the big rocket and carried an array of sensing and evaluation equipment for telemetry acquisition from the ground.

In addition to the untried cluster of six RL-10 liquid hydrogen engines for the S-IV, the Block II Satluns relied on uprated, 836 000-newton (188 000-pound) thrust H-1 engines, that gave the first stage a total thrust of slightly over 6 672 000 newtons (1.5 million pounds). Further, the new engines powered an improved S-1 first stage. The length of the propellant containers, for instance, had been increased to provide additional propellants for the uprated engines. Despite the added weight penalty of



Top left, Saturn I SA-4 rises from the launch pad on 28 March 1963. The last of the Block I vehicles, it has no aerodynamic fins as does SA-5, which sits on the pad at top, right. At left is an artist's conception of S-IV stage separation in space, with the six RL-10 engines kicking the payload into orbit.

the extended container length, there was an overall gain in efficiency of the Saturn I first stage because of numerous changes. These included, for example, weight savings through simplification of the propellant interchange system that lessened the amount of residual fuel and oxidizer trapped in the propellant interchange lines. Heightened confidence in the reliability of the H-1 engines enabled reduction of the hold-down time at launch from 3.6 seconds to 3.1 seconds; this savings shifted an additional 0.5 second of maximum boost to the powered flight phase, thereby enhancing the vehicle's performance. Efficiency of propellant depletion was also increased as a result of experience and numerous subsystems changes. The first SA-1 vehicle used 96.1 percent of its fuel, for example; by the time of the flight of SA-10, the use had reached 99.3 percent. Payload capability was also increased by reducing the amount of pressurants on board. The height of the Block II rockets

QUALIFYING THE CLUSTER CONCEPT

varied with the different missions they performed. With a Jupiter nose cone, SA-5 was about 50 meters high, but the remainder of the Block II vehicles, SA-6 through SA-10, carried prototype Apollo capsules and other payloads, which stretched them to approximately 57.3 meters.⁴

Although electronic instrumentation and telemetry provided reams of pertinent information on the health and performance of the rocket during a mission, flight-test personnel needed visual documentation as well. For this reason, the Saturn vehicles all carried an invaluable array of visual instrumentation equipment. The Block II series continued the visual instrumentation that was begun during Block I flights. MSFC engineers wanted very much to know about the behavior of propellants within the vehicle during flight, so a number of different visual instrumentation systems were carried. Great attention was given to on-board television systems. Work with on-board TV began at MSFC early in 1959 under the cognizance of the Astrionics Division. Research emphasized the development of a compact and extremely rugged camera to stand up under the punishment of liftoff, boost phase, and free trajectory coast in extreme temperature and pressure environments. MSFC tried out the system on 31 January 1961 on the Mercury-Redstone that carried the chimpanzee Ham. The real-time, high-resolution transmitting system worked very well from liftoff across the optical horizon to about 320 kilometers distant. At the same time, the MSFC group was perfecting multiple-camera, single-transmitter equipment for the Saturn I missions; it became operational just prior to SA-1 in the fall of 1961. The system offered "real-time display and permanent storage of pictures televised from the vehicle during test flight." As mounted on SA-6, for example, two camera locations were utilized. On the ground, a videotape recorder and a kinescope recorder provided real-time viewing and storage capability. To identify each picture image, the kinescope recorder system included a digital key, indicating the camera position and time-of-flight reference. Within five minutes of a completed flight, high-resolution individual shots could be available for study.⁵

Television was originally selected for use on rockets because recovery of motion picture film seemed uncertain. Still, the TV units had limitations because a number of critical vehicle functions were not compatible with television camera operations and imagery. For this reason, the Saturn I flights also incorporated motion picture coverage of test flights.

A technique to incorporate such coverage was successfully demonstrated during the Redstone program in 1961 when inflight photographic instrumentation captured the separation of a warhead from a Redstone rocket booster. Early in the Saturn development program, investigators recognized the need for a similar photo system for visual analysis of phenomena that could not be simulated during ground testing or acquired through vehicle telemetry. Plans provided for inflight

STAGES TO SATURN

motion picture and television coverage for the first stage of the SA-1 mission in October 1961 on the basis of the Redstone camera technology. Lack of time and money prevented use of such equipment for the first Saturn launches, and effort was redirected toward the mission of SA-5, the first live, two-stage Saturn I. Responsibility for the camera became a joint program of MSFC's Astrionics Laboratory and the Propulsion and Vehicle Engineering Laboratory. With approval for the project in October 1961, Marshall named Cook Technological Center, a division of the Cook Electric Company of Chicago, as the major contractor. Cook Technological Center then proceeded with the development and manufacture of jettisonable and recoverable camera capsules to be flown on SA-5, 6, and 7.

The camera capsules consisted of three sections: the lens compartment, with camera lens and a quartz viewing window; the combined camera and its control unit in a separate compartment; and a recovery compartment, housing descent stabilization flaps and a paraballoons for descent and flotation, a radio and light beacon for aid in recovery operations, and more conventional recovery devices such as sea-marker dye and shark repellent. The capsules were designed to cope with the stresses of powered flight, ejection, reentry, impact into the sea, and immersion in saltwater. Four model "A" capsules were positioned to record external areas of the Saturn vehicle, facing forward. Four more model "B" capsules were mounted in an inverted position to record the phenomena inside designated LOX tanks and around the interstage between first and second stages. For the "B" models, technicians linked the cameras with fiberoptic bundles to transmit images from remote locations and used incandescent lights and strobe systems for illumination. Engineers preferred to use color film whenever possible because it provided a better three-dimensional image than the gray tones of the black and white film. One camera used an extremely fast and sensitive black and white film to record phenomena inside the center LOX tank because of the lighting inside the tank.⁶

The launch of SA-5, 29 January 1964, was what NASA liked to call "a textbook launch." As the first Block II vehicle, the SA-5 recorded a number of firsts: first S-IV stage to fly, first guidance and control packages, and first successful stage separation. The SA-5 was the first Saturn using uprated engines, marked the first successful recovery of motion picture camera pods, and was the first orbital Saturn vehicle.

Although SA-6 got off the launch pad without a hitch, it caused a moment of concern among mission controllers when one of the H-1 engines inexplicably shut off prematurely. Unlike SA-4, this was not part of the programmed flight, but the Saturn performed beautifully, proving the engine-out capability built into it by Marshall engineers. With hardly a perturbation, the vehicle continued its upward climb; stage separation and orbit of the S-IV upper stage went as planned. Telemetry pinpointed

QUALIFYING THE CLUSTER CONCEPT

the engine problem in the number 8 engine turbopump, which shut down at 117.3 seconds into the flight. When telemetered information was analyzed, engineers concluded that the teeth had been stripped from one of the gears in the turbopump, accounting for the abrupt failure of the engine. Luckily, Marshall and Rocketdyne technicians, through previous ground testing of the turbopump, had already decided that its operating characteristics dictated a modified design. A change had already been planned to increase the width of the gear teeth in this particular turbopump model, and the redesigned flight hardware was to fly on the next vehicle, SA-7. Consequently, there were no delays in the Block II launch schedule and, incidentally, no further problems with any of the H-1 engines in flight.⁷

Otherwise, the flight of SA-6 was eminently successful. The SA-6 was the first to carry a dummy Apollo capsule into orbit, and it tested the capsule by jettisoning the launch escape system tower, part of the Apollo spacecraft hardware development. The performance of the Block II series progressed so well that the Saturn I boosters were declared fully operational by NASA officials after the SA-7 flight (18 September 1964), three launches earlier than expected. The unmanned Apollo spacecraft on board met guidelines for design and engineering, compatibility of the spacecraft and launch vehicle, and operation of the launch escape system. The launch also confirmed the integrity of major critical areas of the launch vehicle such as the Saturn I propulsion systems, flight control, guidance, and structural integrity. For SA-7, the only event that might be considered an anomaly involved the recovery of the cameras. After stage separation, the jettisoned camera pods descended by parachute and landed in the sea, downrange of the expected recovery area. Then Hurricane Gladys blew in and closed the sector. Seven weeks later, two of the ejected SA-7 camera capsules washed ashore, encrusted with barnacles, but with the important films undamaged.⁸ The last three Saturn I vehicles carried a redesigned instrument unit with more sophisticated components that did not require separate, pressurized sections; the result was a lighter and shorter vehicle with enhanced performance. With a different environmental control system, the new instrument unit was the prototype for the Saturn IB and Saturn V vehicles. The most significant feature that set all three vehicles apart from their predecessors was the payload—the unusual, winglike meteoroid technology satellite known as Pegasus.⁹

SATURNS FOR SCIENCE: THE PEGASUS PROJECT

Project Pegasus was something of an anomaly in the Apollo-Saturn program. Responsibility for Pegasus management, design, manufacture, operation, and analysis of results was charged to Marshall Space Flight

STAGES TO SATURN

Center. The reputation of the Marshall center rested not on satellites, but on the launch vehicles designed and engineered by the von Braun team. The Pegasus was also unique because it was the only NASA satellite to use Saturn boosters. It was especially significant from the standpoint of designing later versions of the Saturn vehicles. Data collected by Pegasus would either confirm the ability of existing designs to operate without danger from meteoroid impact or require new designs to cope with the dangers of meteoroid collisions. The Pegasus project was an example of the painstaking scope of the Apollo-Saturn program research and development to avert any sort of serious problem. Finally, the project demonstrated several ways in which the operation contributed to the general store of scientific knowledge, as well as to the design and operation of boosters, spacecraft, and associated systems.¹⁰

Meteoric particles striking the Earth travel at speeds up to 72 kilometers per second. A dust-speck particle, weighing a mere 0.0085 gram, at such a speed packs the energy of a .45-caliber pistol fired point blank. Meteoroid phenomena in the near-Earth space environment commanded serious attention, the more so because many critical moments of manned Apollo-Saturn missions occurred in potentially hazardous zones. The Gemini spacecraft experienced meteoroid impacts many times during a 24-hour period, but the specks encountered in the lower Gemini orbits were too small to cause a puncture in the spacecraft skin. Higher orbits for the Apollo series raised concerns about heavier meteoroid particles. "It is the stuff of intermediate size that concerns a space-vehicle designer," Wernher von Braun emphasized. "Particles of only a few thousandths of a gram, whizzing at fifteen to twenty miles a second, can penetrate a spacecraft's wall or a rocket's tank. They constitute a definite risk." A meteoroid puncture in a gas compartment or propellant tank could cause a serious leak, and in the case of a highly pressurized container create an explosive rupture. Particles also created heat at the moment of impact. With highly volatile propellants aboard, as well as the oxygen-enriched cabin atmosphere, penetration by a burning meteoroid would touch off a destructive explosion. Even without complete penetration, impacts could cause "spalling." The shock of impact with the skin of a spacecraft could eject fragments from the skin's interior surface to ricochet inside the vehicle. These flying fragments raised a serious possibility of danger to a crew or to vital equipment. The need for information was clear.¹¹

Late in 1962, designers of spacecraft of the Apollo-Saturn program had very limited knowledge of the abundance of meteoroids in the vicinity of Earth, where numerous manned flights were planned and where crucial phases of the lunar missions would occur. Astronomers could provide information on meteoroids with mass above 10^{-4} grams, since they could be sighted optically from observatories or tracked by radar. Vehicle sensors like those on *Explorer XVI* provided some statistics

QUALIFYING THE CLUSTER CONCEPT

on the abundance of smaller particles, but the lack of data on the intermediate-sized meteoroids caused persistent doubts, because information on the intermediate range presented configuration criteria "of utmost importance for the design of spacecraft." Pegasus was intended to fill in the gap. As stated in the official report: "The objective of the Pegasus Meteoroid Project is the collection of meteoroid penetration data in aluminum panels of three different thicknesses in near-earth orbits. . . . In fact, the abundance of meteoroids in the mass range 10^{-5} to 10^{-3} will be decisive with respect to the necessary meteoroid protection for future long-duration manned missions."¹²

Attached to the S-IVB second stage, Pegasus deployed in 60 seconds, extending two wings to a span of 15 meters, with a width of 4.6 meters and a thickness of about 50 centimeters. The Pegasus wing mount also supported solar cell panels for powering the satellite's electronics.¹³ In full deployment, the Pegasus in flight exposed about 80 times more experimental surfaces than Explorer meteoroid detectors exposed. The meteoroid impact sensor was a charged capacitor with a thin dielectric, a metal foil on one side, and a sheet of aluminum on the other side. Perforation by a meteoroid caused a momentary short between the metal plates. The discharge burned off any conducting bridges between the two metal layers; thus the capacitor "healed" after each perforation. The shorts, or discharges, were recorded as hits.¹⁴ Special sensors carried by the satellite provided information on (1) the frequency and size of meteoroids capable of damaging the spacecraft structure and equipment, and (2) the direction of the meteoroids as a function of frequency and power of penetration.¹⁵

PEGASUS MISSIONS

Planned as part of the qualification program for the Saturn I rocket, the three Pegasus flights instead assumed the status of completely operational flights following the success of SA-7. On 29 December 1964, Pegasus I, the first meteoroid detection satellite, arrived at Cape Kennedy to join its Saturn I booster, SA-9.¹⁶ The numerical designation of the boosters fell out of sequence because of variations in their manufacturing. After designing and building its own first-stage boosters for the Saturn I program, NASA-MSFC departed from the original concept of work in-house to rely on industrial contractors. Chrysler Corporation became the prime contractor for the S-I first stage of the Saturn I, and Douglas continued to supply the S-IV second stage. In the process of gaining experience, Chrysler's first Saturn booster, SA-8, moved less rapidly through manufacturing and test than the last booster produced by MSFC, SA-9. In retrospect, it seems appropriate that MSFC's last rocket launched the first Pegasus, MSFC's first satellite.¹⁷

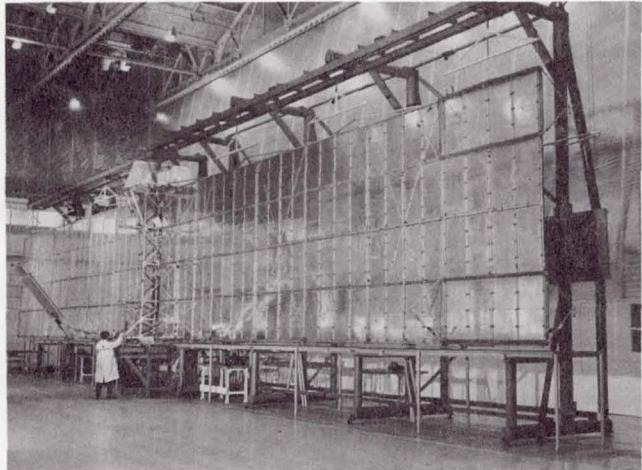
STAGES TO SATURN

To carry the Pegasus aloft, the S-IV second stage and the instrument unit underwent some minor modifications. Because heat absorption could upset the satellite's thermal balance, Douglas supplied the S-IV with a special coat of paint to reduce the heating factor. New equipment consisted of an "auxiliary nonpropulsive vent system" to cut down excessive tumbling and enhance the orbit stabilization. Designers also incorporated the reworked instrument unit. NASA officials scheduled the launch of SA-9 for 16 February 1965, and technicians at Cape Kennedy worked hard to meet their preflight deadlines. With the Pegasus payload shrouded in the Apollo service module and adapter, KSC personnel affixed it to the S-IV second stage on 13 January. The next day, at Launch Complex 37-B, workers finished mating the Apollo command module to the AS-9 vehicle. In their drive for flawless operations, NASA and contractor personnel continued to tinker with the satellite right up to the last minute. On 14 February, only two days before the launch, technicians from MSFC and Fairchild made final changes in the meteoroid detection subsystem.

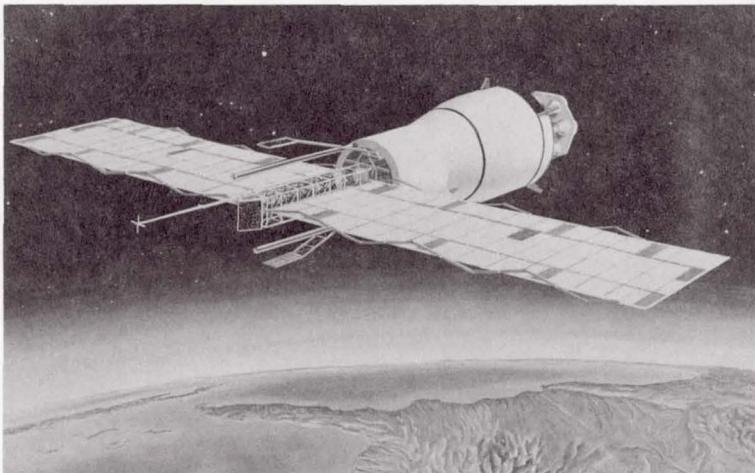
On 16 February, the Saturn I vehicle SA-9 successfully lifted off from Launch Complex 37-B with NASA's largest unmanned instrumented satellite to date. It was the first time a Saturn rocket had been used to loft a scientifically instrumented payload into space. In a flawless mission, the Saturn I put Pegasus into orbit, and inserted the command module into a separate orbit where it would not interfere with scientific measurements. A remotely controlled television camera, mounted atop the S-IV second stage, captured a vision of the eerie, silent wings of *Pegasus I* as they haltingly deployed.

Pegasus took 97 minutes to circumnavigate the Earth. From scattered Moonwatch stations, observers reported the magnitude of the satellite as zero to seven as it moved through space.¹⁸ When the residual fuel from the S-IV vented, Pegasus began to tumble, with occasional intense flashes when solar rays glanced off the large wings. With its moderate orbital inclination (31° to the equator), the best path for observation in the United States ran close to Boston and Chicago, but conditions were difficult because the satellite hovered only a few degrees above the southern horizon and the extensive slant range made sightings difficult. However, at the Smithsonian Institution's observatory in South Africa, visual sightings were easily made. As the sun's light glittered on the outstretched wings of Pegasus, observers caught flashes of reflected light that lasted for as long as 35 seconds.¹⁹

Because Pegasus relied on solar cells for power, NASA spokesmen hoped that the satellite would work at least a year, but with 55 000 parts in the system, some project officials were reluctant to predict a full 12-month lifetime, at least for the first vehicle. In the beginning, everything seemed to be working well. On its fourth orbit, scientists thought they caught the first signal of a meteoroid hit, and by the end of



Above, a Fairchild technician checks out the extended Pegasus meteoroid detection surface in March 1964. At right is an artist's conception of Pegasus in orbit with meteoroid detector extended.



the first seven days of flight, they were eagerly anticipating the first full reports read out from the Pegasus memory banks. In the first two weeks, Pegasus indicated almost a score of hits by interplanetary objects. By late May, NASA verified more than 70 meteoroid penetrations. NASA spokesmen unhappily verified extensive failures in the Pegasus satellite as well, but MSFC and Fairchild personnel had just enough time to solve these difficulties before the launches of Pegasus II and III.²⁰

The second of the meteoroid satellites, Pegasus II, arrived at KSC on 21 April 1965. The final countdown for SA-8 began on the afternoon of 24 May. With a scheduled 35-minute hold, the countdown ticked on without a hitch into the early morning of the launch, 25 May. The flight of SA-8 marked two especially notable departures from past experiences in the Saturn program. For one, the S-1 booster was manufactured by Chrysler, and Saturn flew with a first stage supplied by a contractor for the first time. It symbolized the end of an era for the von Braun team and the long-standing arsenal "in-house" philosophy transferred from the

STAGES TO SATURN

old ABMA days to the young space program of NASA. For another, SA-8 blasted off at 2:35 a.m. in the first night launch of a Saturn rocket. Highlighted against the dark night skies, the winking lights of the launch tower and the blinding glare of the floodlights around the base of the launch pad gave the scene an unusual new fascination. The darkness gave even higher contrast to the fiery eruption of ignition and the lashing tongues of fire during liftoff. Always awesome, the thundering roar of the Saturn I's ascent seemed mightier than ever before, as it seared its way upward through the dark overcast above the Atlantic. NASA officials timed the launch to avoid conflict in the communications with *Pegasus I*, still in orbit. Both satellites transmitted on the same frequency, and the fiery night launch of *Pegasus II* put the second satellite at an angle of 120°, one-third of an orbit apart from the first.²¹

The launch illustrated the accuracy of the propulsion systems and confirmed the reliability of the flight electronics, which were improved in successive launches of the Saturn I series. Wernher von Braun praised the flight as "a lesson in efficiency," and George Mueller, Associate Administrator for Manned Space Flight, commented that the flight was very significant to future space flights, with their need for very close timing for rendezvous missions. *Time* magazine considered the flight from other points of view. The magazine approvingly reported the success of the cluster concept used on the S-1 booster and the faultless performance of the second stage with its six RL-10 engines: "The smooth success of last week's launch suggests that LH₂ has at last become a routine fuel." The editors acknowledged the need for more information on meteoroid hazards in space flight but found the greatest significance in the launch itself. "Far more encouraging for space exploration," said *Time*, "was the smoothness with which the many-tiered rocket was dispatched into the sky." So often a rocket vehicle spent weeks or month on the pad with delays, but no setbacks occurred in the launch of SA-8, "which left its pad as routinely as an ocean liner leaving its pier."²² The second Pegasus satellite began returning data in short order. Within one day after launch, it indicated two meteoroid penetrations. Modifications on *Pegasus II* included successful refinement of the detector electronics and a handful of minor readjustments. The second Pegasus experienced some troubles during its mission, primarily with the analog and digital telemetry channels. Technicians finally smoothed out the digital failure, and even though the analog transmissions continued intermittently, they worked well enough to rate the mission a success. Tracing the source of trouble, workers finally decided it originated in a thunderstorm during preparation of the spacecraft on the pad, because the wettest section contained the circuit failure.²³

On 21 June 1965, the Apollo command module and associated hardware arrived at KSC for the launch of the last meteoroid detection satellite, *Pegasus III*. With planned modifications for Launch Complex

QUALIFYING THE CLUSTER CONCEPT

37-B to service the uprated Saturn IB launch vehicle, NASA officials decided to move the flight of SA-10 ahead to 30 July to avoid delays in both the launch and the modifications of the launch pad. Technicians ran a series of checks to verify panel deployment and compatibility of systems, then joined *Pegasus III* to the instrument unit of the SA-10 vehicle. On 27 July 1965, the KSC launch crew ran an uneventful and successful countdown demonstration test for SA-10, the last Saturn I. By 29 July, the final phase of the launch countdown was under way and proceeded with no technical holds to liftoff on the next day. The SA-10 vehicle performed flawlessly, inserting the command module and *Pegasus III* into the planned orbital trajectory. On the basis of data from all three meteoroid detection satellites, NASA spokesmen announced in December that the Apollo-Saturn structure would be adequate to withstand destructive penetration by meteoroids during space missions. The *Pegasus* project was successful.²⁴

The information gathered by the *Pegasus* trio included much more than variations in theoretical meteoroid penetration data. In his capacity as Director of the Space Sciences Laboratory, Ernst Stuhlinger praised the secondary results, which returned scientific data valuable to the design and engineering of future spacecraft, as well as knowledge of specific scientific nature. "It sometimes occurs that an experiment, planned for one specific objective, provides observational results far beyond the single-purpose mission for which it was originally conceived," he said. "Project *Pegasus*, which has the primary objective of measuring the near-Earth environment, is an example in case." For the benefit of spacecraft designers, the 65 000 hours accumulated in all three missions provided significant and valuable data on meteoroids, the gyroscopic motion and orbital characteristics of rigid bodies in space, lifetimes of electronic components in the space environment, and thermal control systems and the degrading effects of space on thermal control coatings. For physicists, the *Pegasus* missions provided additional knowledge about the radiation environment of space, the Van Allen belts, and other phenomena.²⁵

The last of the meteoroid detection satellites, *Pegasus III*, carried a captivating experiment, one of the first intended to be left in space, to be personally retrieved by an astronaut at some future date. Eight large detector segments were removed from the *Pegasus* wings, replaced with "dummy" panels and 48 temporary coupons, cut from samples of the detector surfaces. The coupons, in turn, carried 352 items of test materials and thermal samples, some of them in use, others considered as candidates for future application. Examples of the test items included aluminum skin specimens, ranging from sandblasted and anodized surfaces to pieces covered with luminescent paint and gold plate. The launch of *Pegasus III* put it into an orbit of 530 kilometers. After 12 months, NASA planners expected the orbit of *Pegasus III* to decay some,

STAGES TO SATURN

putting it in position for a potential rendezvous with a Gemini spacecraft. Theoretically, one of the Gemini astronauts could emerge from the Gemini capsule, maneuver himself to the Pegasus wings, recover a selected group of test specimens, and return to the spacecraft. With the return of the astronaut's armful of samples to Earth, scientists could not only make direct studies of the effect of meteoroid impacts on metals in interplanetary space but also examine specimens of meteoroids taken directly from the space environment. Unfortunately, the experiment was never possible during Gemini, and the final Pegasus reentered the atmosphere on 4 August 1969. Its destruction during reentry brought an untimely end to an intriguing experiment.²⁶

SATURN I IN RETROSPECT

In terms of rocket development, the series of Saturn I launches was remarkably successful. Most rocket programs had severe teething troubles early in the game; up to two or three dozen test shots and loss rates of 50 percent were not out of the ordinary. True, the Saturn I used engines and tanks extrapolated from earlier programs, but uprating the H-1 engine had brought difficulties, and a cluster of this magnitude was untried. Moreover, the later Saturn missions introduced a sizable new LH₂ upper stage, powered by a cluster of six RL-10 engines.

For all this, there seems to have been persistent criticism of the Saturn I series of launches. Basically, it appeared to be a multimillion-dollar launch vehicle program with no significant missions or payloads. Even before the launch of SA-2 in the spring of 1962, NASA had announced the Saturn V. It was this vehicle, not Saturn I, that had the mission and payload that counted: a lunar voyage with a payload equipped to land men on the moon and get them back again. As a preliminary to Saturn V missions, plans were already in progress for the Saturn IB, which would test a Saturn V third stage in orbit and begin qualification of crucial hardware such as the command module and lunar module.

The Saturn I, as one NASA historian has written, was a "booster almost overtaken by events." A number of individuals, within NASA as well as on the outside, felt that Project Highwater and, to a lesser extent, Project Pegasus were makeshift operations to give Saturn I something to do and to placate critics who complained that the Saturn was contributing little to science. There is probably some truth in these allegations. Highwater in particular seems to have been an impromptu operation, revealing nothing new. Although NASA literature solemnly referred to scientific aspects, von Braun called Highwater a "bonus experiment," and noted that the water was already aboard Saturn I stages as ballast.²⁷

With hindsight, the apparently superfluous Saturn I launches still contributed to the Saturn program, underscoring the innate conserva-

QUALIFYING THE CLUSTER CONCEPT

tism of Marshall Space Flight Center. Aware of potential early failures in a launch series, MSFC evidently planned for several, but to make the series as successful as possible, Marshall also went into each launch with vehicles tested and retested to the point where the possibility of failure was virtually eliminated. Marshall's own thoroughness made the remarkable string of 10 successful launches seem unnecessarily redundant. In any case, the launches verified many concepts for systems and subsystems applied to later Apollo-Saturn missions, provided valuable experience in the operation of LH₂ stages, demonstrated the validity of the cluster concept, and tested early versions of Saturn guidance and control. Payloads for the Saturn I launches may not have been as dramatic as those for other vehicles, but Saturn I missions, overall, were nevertheless beneficial.

In a strict sense, the series of Pegasus launches was not very earthshaking. None of the three satellites promoted any fantastic new discoveries; no dramatic design changes occurred in either the Saturn launch vehicles or the Apollo spacecraft as a result of unexpected information about meteoroid penetration. The value of the Pegasus involved a positive, rather than a negative, reading of the test results. The satellites confirmed basic estimates about meteoroid frequency and penetration in the operational environment of the Apollo-Saturn vehicles. This confirmation provided a firm base of knowledge to proceed with basic designs already in the works. In fact, it was good that the Pegasus series did not turn up significantly different data, which would have entailed costly redesign and additional time and research into meteoroid phenomena as related to boosters and spacecraft. Instead, the effect was to add to the growing confidence of Apollo-Saturn designs already in process and to permit NASA to plunge ahead toward the goal of landing man on the moon within the decade. It would have been easy to dismiss what was, in fact, a successful developmental phase in the overall Apollo-Saturn program.²⁸

In terms of subsequent programs, the legacy of Pegasus included significant contributions in the development of thermal coatings used on many major satellites, as well as on the Apollo spacecraft. The Pegasus also had a significant impact on the development of the communications satellite (comsat) project, because the results indicated that the comsat satellites would indeed have a profitable lifetime in orbit, the probability being high that they would survive or escape damage from meteoroids. Wernher von Braun was emphatic on this point: "I would say the Pegasus data have really become the main criteria of spacecraft design, ever since Pegasus, for all manned and unmanned spacecraft."²⁹

JUNIOR PARTNER TO APOLLO: SATURN IB

The Saturn IB represented significant advances toward the hardware and techniques to be used in lunar landings. S-IB first stages included a

STAGES TO SATURN

number of modifications to increase the overall vehicle performance, as compared with the S-I series. The aerodynamic fins were further modified, and changes in fabrication techniques saved considerable weight (see chapter 3). The eight H-1 engines were uprated from 836 000 to 890 000 newtons (188 000 to 200 000 pounds) of thrust each. Most importantly, the Saturn IB missions provided an opportunity to flight-test the first Saturn V hardware. The S-IVB upper stage with its single J-2 engine was nearly identical to the upper stage carried on the Saturn V, and the same was true of the instrument unit (see chapter 8).³⁰

Saturn IB missions began with the unmanned launch of AS-201 from KSC Launch Complex 34 on 26 February 1966. With both stages live, the vehicle made a successful 32-minute suborbital flight, reaching an altitude of over 480 kilometers with impact into the south Atlantic about 320 kilometers from Ascension Island.

The primary tests concerned separation of the spacecraft, followed by the command module's reentry into Earth's atmosphere. The maneuver successfully demonstrated that the command module's heat shield could withstand the intense temperatures created by atmospheric friction during reentry. The first Saturn IB experienced relatively few problems in flight, although the mission was nearly canceled during countdown. Bad weather delayed the launch date for three days, and on the day of the liftoff, launch officials postponed the firing command for three hours while technicians did some trouble-shooting on several last-minute technical problems. The most serious difficulty involved the gaseous nitrogen purge system that cleaned out the engines and the related machinery prior to launch. At T-4 seconds, the gaseous nitrogen pressure limits had dropped below the red-line level and an automatic cutoff sequence was started. After resetting the equipment and starting the countdown once more, at T-5 minutes engineers perceived the problem again and requested a hold. Engineers estimated that it would possibly take two hours of work to recheck and reset all the equipment. Reluctantly, the recommendation was made to scrub the launch. Still searching for options, a group of launch crew engineers suggested a different test of the system to assess other alternatives, and stage engineers agreed; so the countdown was restarted at T-15 with the gaseous nitrogen pressures reset at different levels. The countdown and launch were finally completed successfully.³¹

Saturn IB missions carried inflight visual instrumentation perfected during the Saturn I missions. Only two movie cameras were used, however, and a ribbon parachute was added to the capsules to slow their descent even more, because some capsule damage had occurred on the SA-6 mission. Typically, the cameras were located atop the first stage to record stage separation and ignition of the S-IVB second stage. On the AS-201 flight neither of the parachutes worked properly, and the Air Force recovery team found only one capsule. On the other hand, the

QUALIFYING THE CLUSTER CONCEPT

guidance and control system performed as expected, telemetry was good, and no structural problems were discerned. The propellant utilization system worked as designed: the LOX and LH₂ were depleted simultaneously. All things considered, the two-stage Saturn IB vehicle achieved a notable inaugural flight.³²

The second launch of the Saturn IB series, on 5 July 1966, carried an out-of-sequence number designation, AS-203. Originally scheduled for the second launch in the series, AS-202 became third in line to gain additional time for checkout of its Apollo spacecraft payload. NASA made the announcement in April, explaining that the AS-203 mission primarily involved launch vehicle development. Mission objectives for the second Saturn IB launch concentrated on the orbital characteristics and operation of the S-IVB second stage, so the vehicle had a simple aerodynamic nose cone in place of the Apollo spacecraft. Launch officials considered the second stage itself, with 10 metric tons of liquid hydrogen aboard, as the payload. Testing was scheduled to gain further information about liquid hydrogen in the orbital environment and about procedures for reignition of the S-IVB in orbit, a requirement for Saturn V missions in the future. The reignition sequence was not to be live but simulated with the S-IVB and J-2 engine systems. In an attempt to telescope development of the stage and engine operations, last-minute consideration was given to an actual restart of the J-2 engine. A number of people within Marshall Space Flight Center, however, opposed restarting the J-2 because that would unduly complicate the developmental flight. In a letter to Major General Samuel C. Phillips, Eberhard Rees estimated that a complete restart sequence would require an additional 1800 kilograms of liquid oxygen and 1400 kilograms of other equipment and provisions and would compromise the main test goals of the behavior of liquid hydrogen in the orbital environment as well as other test procedures. "Douglas and MSFC are confident that a successful AS-203 mission, as presently defined," said Rees, "should establish whether or not successful restarts can be accomplished on Saturn V missions."³³

For reignition under weightless conditions, fuel and oxidizer had to be settled in the bottoms of the propellant tanks. Engineers hoped to achieve this through the use of the hydrogen continuous vent system. The venting gas imparted thrust which pushed the propellants to the bottom of the tanks. This thrust could be augmented by occasionally opening the liquid oxygen tank propulsive vent valve. To study the stability of the liquid hydrogen in orbit and to check settling of the liquid hydrogen at the bottom of the tanks, the S-IVB carried a pair of TV cameras mounted inside the tank. Prior to launch, a checkout of the TV system uncovered trouble in one of the cameras. After a hold of almost two hours, NASA engineers decided not to postpone the launch any longer and the vehicle lifted off with only one of the cameras expected to work. Fortunately, the remaining camera functioned well, and the

STAGES TO SATURN

images verified the hopes for proper propellant behavior during venting and for settling of the propellants prior to reignition. Motion picture color coverage of stage separation, recovered from the ocean in one of the camera capsules, was also of high quality and showed the desired performance.

Following the satisfactory TV coverage of the behavior of liquid hydrogen under weightless conditions and a simulated restart of the J-2, technicians proceeded with the plan to break up the S-IVB stage in orbit. This rather dramatic procedure was intended to verify ground tests that had been carried out on structural test models at Douglas facilities on the West Coast. Investigators from Douglas and MSFC wanted to establish design limits and the point of structural failure for the S-IVB common bulkhead when pressure differential developed in the propellant tanks. Ground tests were one thing; the orbital environment of space was another. Breakup occurred near the start of the fifth orbit when the common bulkhead failed and the stage disintegrated. The results confirmed the Douglas ground experiments; the S-IVB stage could withstand tankage pressure differentials over three times that expected for normal mission operations.³⁴

AS-202, launched on 25 August 1966, returned to the suborbital mission profile because the primary purpose was to test the heat shield on the command module (CM). Extensive holds, taking up three days, had been caused by problems with the spacecraft and ground telemetry. With the problems finally resolved, the AS-202 vehicle lifted off in a flawless launch. The S-IVB successfully tested its ullage rockets and ignited as planned despite some minor valve malfunctions in the recirculation system of the J-2. Separation of the S-IVB and the CM caused oscillatory motions of the S-IVB, which could have made for tricky maneuvers for CM docking with the lunar module (LM) in manned missions, but the S-IVB auxiliary propulsion system brought the stage back under control. In accordance with the planned profile, the CM made a "skipping" reentry to raise the heat loads and subject the heat shield to maximum punishment. Recovery of the scorched CM occurred near Wake Island in the Pacific Ocean.

The success of the first three Saturn-IB missions heightened expectations for the first manned launch, scheduled for 21 February 1967 as AS-204. The three-man crew included Virgil I. Grissom, Edward H. White II, and Roger B. Chaffee. During a checkout of the complete vehicle on the launch pad at KSC's Launch Complex 34 on 27 January, a flash fire erupted inside the CM. Trapped inside, the three astronauts died.³⁵

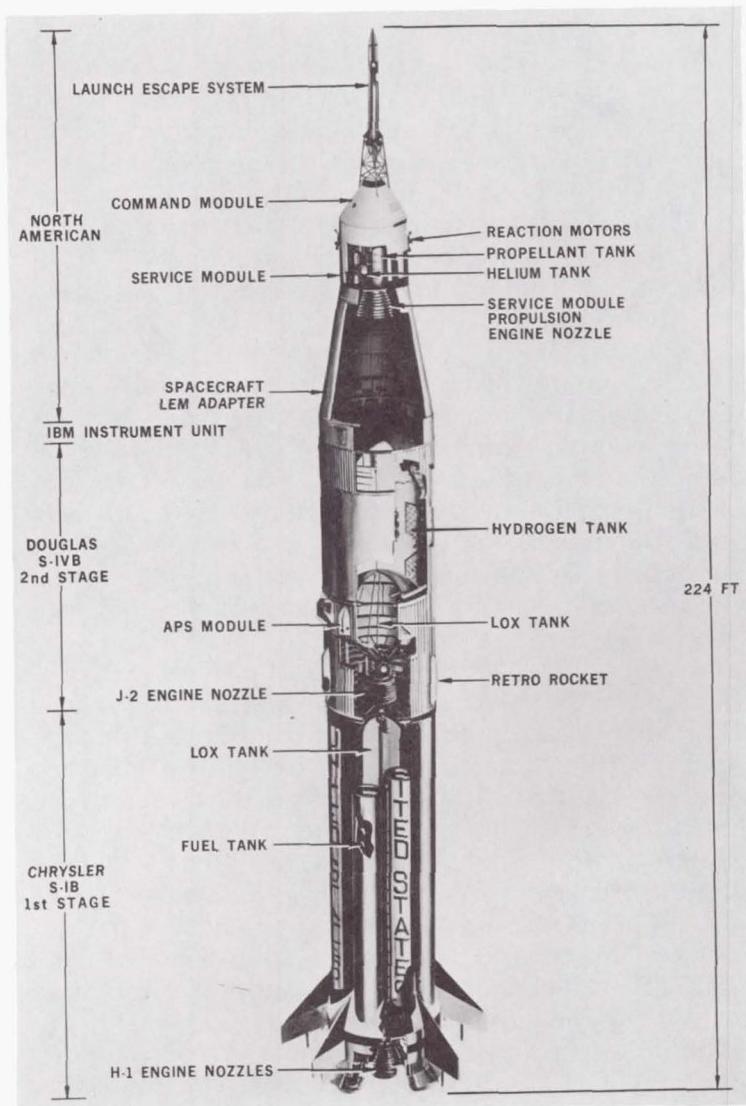
The exhaustive investigation of the fire and extensive reworking of the CMs postponed any manned launch until NASA officials cleared the CM for manned flight. Saturn IB schedules were suspended for nearly a year, and the launch vehicle that finally bore the designation AS-204 carried an LM as the payload, not the Apollo CM. The missions of AS-201

QUALIFYING THE CLUSTER CONCEPT

and AS-202 with Apollo spacecraft aboard had been unofficially known as Apollo 1 and Apollo 2 missions (AS-203 carried only the aerodynamic nose cone). In the spring of 1967, NASA's Associate Administrator for Manned Space Flight, Dr. George E. Mueller, announced that the mission originally scheduled for Grissom, White, and Chaffee would be known as Apollo 1, and said that the first Saturn V launch, scheduled for November 1967, would be known as Apollo 4. The eventual launch of AS-204 became known as the Apollo 5 mission (no missions or flights were ever designated Apollo 2 and 3).³⁶

As *Apollo 5*, the original AS-204 vehicle lifted off from Launch Complex 37 at KSC on 22 January 1968 in an unmanned test of the lunar module in Earth orbit. The LM was enclosed in a spacecraft-lunar-module adapter and topped by an aerodynamic nose cone in place of the Apollo command and service modules (CSM). Evaluation of the LM included ignition of the descent and ascent stages and LM staging and structures. Engineers also intended to conduct an S-IVB propellant dumping experiment in orbit, following separation of the stage from the LM. Dumping was considered necessary to make the S-IVB safe before docking of the CSM with the S-IVB-attached LM.

Some months prior to the AS-204 mission, NASA planners realized that the vehicle was going to be sitting stacked on pad 37 for a considerable period of time awaiting the arrival of the LM. NASA took advantage of the opportunity to monitor the conditions of the launch vehicle over a long period of time, as it stood on the pad exposed to the elements on the Florida coast. On 7 April 1967, the first stage had been erected; the second stage and the instrument unit were added in the next four days. Marshall and contractor personnel devised a detailed set of criteria for periodic inspections of the vehicle starting that same month. No components had to be replaced because of corrosion; advance planning had paid off. The vehicle was under constant nitrogen purges to protect the engine compartment and other equipment areas from the salty atmosphere. The vehicle propellant tanks were also kept under pressure with dry nitrogen. These procedures were maintained during a kind of musical chairs operation as the LM and its associated hardware were moved in and out, off and on, for several weeks. After arrival of its ascent and descent engines and their mating, they had to be taken apart in August to repair leaks in the ascent engine. Then the two stages were mated again until September when a new leak required demating. Several items of LM hardware had to be shipped back to the contractor for additional work. The ascent and descent engines of the LM were put together again in October, and tests were run until November when the spacecraft was taken to the pad and mechanically mated with the booster. The flight readiness tests were not accomplished with the total vehicle until late in December with the LM in position, nearly nine months after the launch vehicle had been put in place on Launch Complex 37.

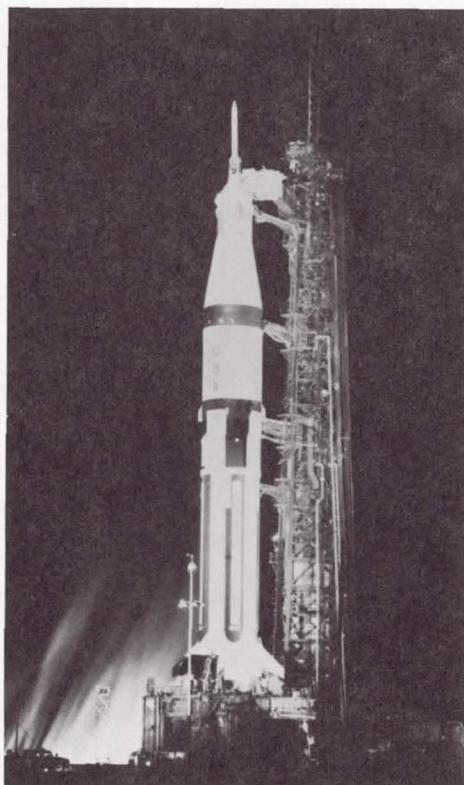
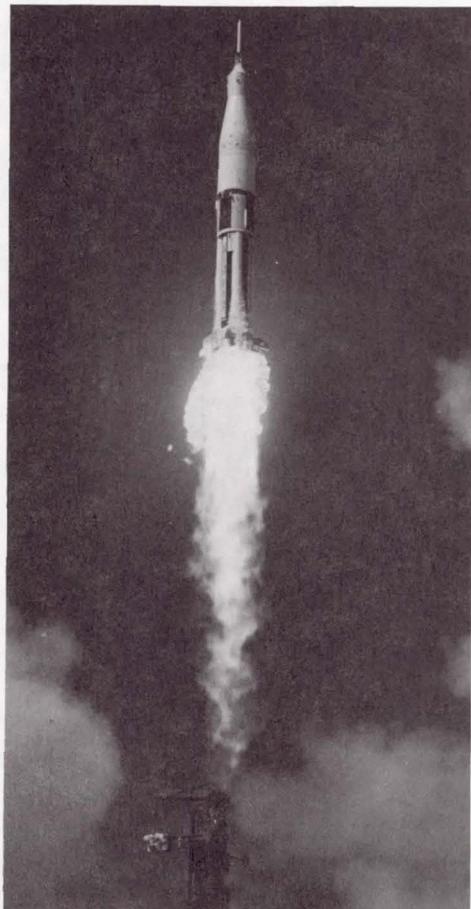


Above is a cutaway drawing of the Saturn IB launch vehicle. At right, the first S-IB rises successfully from KSC's Launch Complex 34 on 26 February 1966. At far right, the first manned Saturn IB, Apollo 7, is shown on the launch pad at night, poised for takeoff the next day, 11 October 1968.

QUALIFYING THE CLUSTER CONCEPT

The successful mission of AS-204 in January 1968 was therefore very gratifying to the launch vehicle crews as well as to the LM crews. Both the first and the second stages performed well, and a new liquid-hydrogen-recirculation-chilldown control valve on the S-IVB worked without a hitch, eliminating a potential problem uncovered on the AS-202 mission. The guidance and telemetry systems met requirements, the panels protecting the LM deployed, and the LM separated from the S-IVB with no trouble. During the S-IVB liquid oxygen dump and liquid-hydrogen dump experiments, the exhausting of propellants through the J-2 engine caused minor attitude variations in the stage, but these were corrected by the thrust vector control system and the auxiliary propulsion system modules. On the morning of 23 January 1968, the S-IVB stage disintegrated during reentry. AS-204 once more set the stage for the first manned launch in the Apollo-Saturn program: AS-205, known as Apollo 7.³⁷

Launched on 11 October 1968 from KSC Launch Complex 34, the *Apollo 7* had a crew made up of Walter M. Schirra, Jr., Donn F. Eisele, and



STAGES TO SATURN

R. Walter Cunningham. Primary objectives for the mission pertained to the CSM, crew performance, manned mission support facilities for the CSM, and CSM rendezvous techniques. With three astronauts aboard and the necessary provisions to sustain them in orbital flight, the launch of AS-205 marked again an increase in payload capability. Much of this increase came from the reduction of measurement instrumentation from the prior Saturn launches. AS-204 had required 1225 measurements; 720 sufficed in AS-205. The *Apollo 7* spacecraft also was the product of extensive redesign since the disastrous fire the year before. It featured a quick-opening one-piece hatch, an extensive substitution of materials to reduce flammability, and a modification of the cabin atmosphere for testing and prelaunch operations. Even though primary attention centered on the manned aspects of the mission, NASA and Rocketdyne personnel were closely watching the augmented spark igniter lines for the J-2, which had been modified after they failed during the *Apollo 6* mission on 4 April 1968 (see chapter 12).

The ascent of both Saturn IB stages went like clockwork. During the boost phase of the S-IC stage, Schirra routinely reported an instrument readout of the pitch program, and noted, "She['s] running—it's getting a little noisy now." Then Schirra called out the sequence of inboard and outboard shutdown of the H-1 engines, followed by confirmation of S-IVB ignition on cue at programmed thrust levels. In between comments from Schirra that the ride from the S-IVB was "a little bumpy," flight controllers in Houston also caught Schirra's enthusiastic remark, "She's riding like a dream," and a voice from the spacecraft that "the window view is sensational."³⁸ After more than one hour in orbit, the instrument unit initiated the automatic "safing" sequence, which included the propellant dumping operation. Separation of the CSM from the spent S-IVB stage took place on schedule, and the astronaut crew turned the CSM around for the simulated docking maneuver (the AS-205 did not actually carry an LM). As part of the simulated LM rendezvous exercise, the CSM was maneuvered to a station-keeping position near the spent S-IVB stage as it tumbled through space. On 18 October, seven days after liftoff, the S-IVB reentered over the Indian Ocean. The three astronauts completed 163 orbits before successful reentry and splashed down into the Atlantic on 22 October, where they were picked up by teams from the recovery ship *Essex*. The *Apollo 7* mission achieved all primary mission objectives, and the last of the Saturn IB flights was over. NASA intended the AS-201 through AS-205 flights to qualify the Apollo spacecraft, and the requirements had been met. The Saturn IB first stages had also performed as expected, but more importantly the S-IVB upper stage and the instrument unit for the Saturn V were successfully qualified in orbit.³⁹ In less than a year, the space agency expected to land men on the moon. That mission required the giant Saturn V.

QUALIFYING THE CLUSTER CONCEPT

SUMMARY

With the exception of the S-IVB, every stage of the Saturn launch vehicles depended on clustered engines. The feasibility of large, high-thrust engine clusters was demonstrated by the first successful launch of the Saturn I and verified in one mission after another. Later Saturn I flights (the Block II series) proved the feasibility of using liquid hydrogen fuels in Saturn upper stages. The Saturn I series also provided the opportunity to perfect visual instrumentation systems and to try out evolving concepts of guidance and control as well as hardware and software tagged for the manned lunar landing program. Even though the Highwater experiments contributed little to astronautical science, the Pegasus flights yielded pertinent information that confirmed booster and spacecraft designs under way and accumulated scientific data that influenced the design and operations of later manned and unmanned spacecraft.

Introduction of the Saturn IB afforded NASA the opportunity to flight-test important elements of Apollo-Saturn flight hardware. This included the S-IVB upper stage, the instrument unit, the command and service modules, and the lunar module. During the Saturn IB missions, operations planned for the Saturn V were given a trial run, including orbital coast and restart of the S-IVB and stage separation of the S-IVB and lunar module. The orbital operations and restart of the J-2 engine subjected the instrument unit to the kind of sequencing critical for future lunar missions, and advanced telemetry and visual instrumentation yielded knowledge of the behavior of cryogenic propellants (particularly liquid hydrogen) in orbit.

Finally, the Saturn IB powered the first manned Apollo mission, *Apollo 7*. This manned, Earth-orbital mission cleared an important hurdle before the towering Saturn V lifted a similar payload and steered a course for the moon.

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12

The Giant Leap

Vehicle AS-501, the first Saturn V, lifted off from Launch Complex 39 at the Kennedy Space Center on 9 November 1967. After several weeks of trial and error, the launch capped a countdown that experienced no serious holds or delays. The prime mission objectives for the *Apollo 4* launch vehicle were to verify the first "all up" test of the Saturn V, including all three stages and the instrument unit. The mission objectives also emphasized the qualification of Launch Complex 39 and its ground support equipment, as well as the first orbital reignition of the S-IVB third stage as configured for the Saturn V. The launch of *Apollo 4* included a number of "firsts." For TV viewers, the most visible events were the ignition and liftoff of the vehicle itself, the word from Mission Control in Houston that the spacecraft had entered its simulated lunar trajectory, and the successful reentry and splashdown of the command module. However, as mission director William C. Schneider remarked, these events represented only the tip of the iceberg. "Most of the things we were proving were below the surface," he explained, "not readily apparent to public view."¹

Before an airplane entered operational service, hundreds or even thousands of hours of flight testing proved its air worthiness. For each Apollo-Saturn launch, every component aboard the vehicle was making its first and last flight. For this reason, the weeks, months, and years of ground testing were necessary, and for this reason, the vast array of telemetry was necessary to evaluate the performance of parts and systems that could never be flown again or even recovered for postflight analysis.

STAGES TO SATURN

ALL-UP: THE MUELLER MODE

The AS-501 flight had tremendous significance. It was not only the first Saturn V but it also tested several major systems for the first time in an "all-up" configuration. As one observer described it, "The all-up concept is, in essence, a calculated gamble, a leap-frogging philosophy which advocates compression of a number of lunar landing preliminaries into one flight. It balances the uncertainties of a number of first-time operations against a 'confidence factor' based on the degree of the equipment reliability achieved through the most exhaustive ground-test program in aerospace history." If NASA had followed prior custom, the S-IC first stage might have been launched by itself, testing the concept of the five clustered F-1 engines, each of which had a thrust nearly equal to that of the entire first stage of the Saturn IB. Then a two-stage vehicle would be launched to try out the clustered J-2 engines of the liquid-hydrogen-fueled S-II second stage. Next the three-stage booster would be launched, and finally the entire Apollo-Saturn vehicle including the CSM. This program would have entailed four separate flights, 12 months extra for preflight preparations, and analysis of postflight data for each launch—all this running into hundreds of millions of dollars.²

The concept of the all-up launch did not originate with von Braun or with MSFC, but came from the experience of George E. Mueller, who took up his new duties as Director of the Office of Manned Space Flight for NASA on 3 September 1963. When Mueller took office, NASA was faced with extreme budgetary pressures. The request submitted originally to President Kennedy had totaled \$5.75 billion. In the hectic months following Kennedy's assassination, President Johnson had a very short time for making a multitude of decisions and experienced heavy pressure from Congress to reduce federal expenditures. One influential senator, not a friend of the space program, informed the President that unless NASA expenditures were kept under \$5 billion for the next year, Johnson would lose the senator's vote for the tax bill—and the President wanted that bill very much. These financial pressures on the Johnson administration constitute one reason for all-up testing. As James Webb recalled, "Under these circumstances, NASA made a complete reevaluation of its plans for the NASA program and decided to revise it, going to the very advanced and, to some, risky approach of the 'all-up systems test' procedure for the Saturn V-Apollo combination." It seemed to be the only way to achieve the lunar landing within the decade. Moreover, it imposed a stronger discipline on the contractors and on NASA itself. Even so, Webb admitted, "It was a very bold move."³

Obviously, budgetary constraints played a large role in the all-up decision. On the other hand, this procedure also matched Mueller's background in rocket development and testing. Before joining NASA, Mueller had been with the Space Technology Laboratories in Redondo,

California, where he had been in charge of a number of technical operations for various Air Force missile programs. These included the Thor, Atlas, Titan, and Minuteman ballistic missiles. The all-up concept had been introduced in the development of the Titan II missile and was being written into the development plan for the Minuteman ICBM.⁴

In the fall of 1963, the flight-test sequence for the Saturn launch vehicles was based on a plan issued by Brainerd Holmes, Mueller's predecessor. The Holmes plan reflected the conservative philosophy of the Marshall Space Flight Center, which tested new vehicles step by step. In the case of the Saturn IB, for example, the plan called for two launches, one in August 1965 with both stages live but still utilizing a guidance system from the Saturn I. The second Saturn IB would be launched late in 1965 with the same configuration, and the operational Saturn IB with a prototype instrument unit was not to be flown until January 1966. The same plan called for the first Saturn V launch in March 1966, with a live first stage, inert second and third stages, and a prototype instrument unit. The second Saturn V launch, scheduled for July 1966, was to have live first and second stages, an inert third stage, and a prototype instrument unit. As Mueller settled into his new job, he came to the conclusion that the financial consequences and the time consumption of the step-by-step approach simply could not meet the national goal of a lunar landing by the end of the decade. "It was pretty clear," Mueller said, "that there was no way of getting from where we were to where we wanted to be unless we did some drastically different things, one of which was all-up testing."⁵

It did not take Mueller long to act. On 1 November 1963, in office less than a month, Mueller dispatched a priority teletype to the directors of the Manned Spacecraft Center, Houston; Launch Operations Center, Cocoa Beach, Florida; and Marshall Space Flight Center, Huntsville: "Subject: Revised manned spaceflight schedule. Recent schedule and budget reviews have resulted in a deletion of the Saturn I manned flight program and realignment of schedules and flight mission assignments on the Saturn IB and Saturn V programs." The teletype directed that the first Saturn IB flight, SA-201, and the first Saturn V flight, AS-501, should comprise all live stages, and both should carry complete spacecraft. Mueller also indicated that he wanted the first manned Saturn IB flight to be AS-203. For Saturn V, he wanted the first manned flight to be AS-503. In other words, Mueller was suggesting that the first manned flights in each series occur on the third launch, instead of the seventh. Mueller asked for responses to his proposed schedule by 11 November and concluded with the comment, "My goal is to have an official schedule reflecting the philosophy outlined here by November 25, 1963."⁶ The arrival of Mueller's teletype at Huntsville caused a furor comparable only to the debate on Earth orbit rendezvous versus lunar orbit rendezvous (EOR-LOR).

STAGES TO SATURN

The first occasion for von Braun to discuss the message with his top staff occurred on Monday, 4 November, at the staff luncheon. A lively and occasionally rancorous debate continued for the next several days. The Mueller idea went against the approach of the von Braun team, steeped in a step-by-step, conservative philosophy of flight testing. Before the V-2 was operational, dozens of test rounds had been fired; many remembered the numerous abortive launches suffered in the early development period of Redstone and Jupiter. The chance of failure on the inaugural Saturn V seemed too high, and the financial risk too great. As recalled by Bob Young, Chief of Industrial Operations at the time, the reaction among von Braun's senior technical staff was "one of shock and incredulity." The general reaction seemed to be, "It is simply not done that way." The meetings, and the debate, continued. Walter Haeussermann, for example, pointed out that it was difficult to predict the rate of success for an all-up launch. How was it possible, for instance, to assign the probability of success or failure for a first stage on the first flight? Other people groused about the limited time available, and there was continuing concern about the workability of liquid hydrogen—particularly in the S-II second stage with its cluster of five engines. There was still some question about the degree of readiness of the instrument unit. One individual close to the discussions at this time, Frank Williams, said that he could not remember anyone who thought it was a good idea or that it would work at all.

The initial consensus at MSFC was to oppose the all-up decision. Bob Young recollects that both von Braun and Rees were low keyed in voicing their doubts, but in the end they sided with Mueller. Rees, in retrospect, stressed the time element in particular. He pointed out that the original approach would have required reconfiguring the launch site for every launch. The time involved in this reworking would have made a landing on the moon within the decade very doubtful. Still, there was considerable ambivalence on the part of the senior staff at Marshall Space Flight Center. Dieter Grau seems to have summed up the situation most accurately. "I'm not aware," he wrote years later, "that a consensus was obtained on this subject in favor of the all-up concept, although I know that Dr. von Braun went on record for the Center supporting this concept eventually. Just as Dr. Mueller could not guarantee that this concept would succeed, the opponents could not guarantee that it would fail. Dr. Mueller wanted to eliminate the additional costs which a more cautious approach would have required and Dr. von Braun decided MSFC should share the risk with him." The decision was declared to be MSFC policy, even though doubts continued to be expressed by many at Huntsville.⁷ Without saying so, von Braun himself still harbored some concerns.

By 8 November, von Braun was ready with the interim response that Mueller had requested. "There is no fundamental reason why we cannot

fly ‘all-up’ on the first flight,” von Braun wrote. Nevertheless, he urged the importance that a “fall back” position should also be maintained, if some problem developed in a technical area with scheduling or in funding before the launch of AS-501.⁸ Before sending the letter, however, von Braun called Mueller, read him the draft and discussed the various issues involved. He reminded Mueller that details were somewhat sketchy, because the program under discussion was a multibillion dollar program with dozens of contractors, and it was difficult to rethink such a radical change and reschedule everything in less than a week. Mueller acknowledged the tentative character of the discussion and was reassured by von Braun’s description of Marshall’s consensus. Stretching things a bit, von Braun told him, “Our development team here with whom we discussed everything in much detail is solidly behind the all-up flight concept.”⁹

Although correspondence between Marshall and NASA Headquarters continued to endorse the all-up principle and in-house memorandums at Huntsville encouraged commitment to it, there was still some sniping from von Braun’s senior management. When Mueller and Robert Seamans, NASA Associate Administrator, visited Marshall early in December 1963, the Saturn V Program Manager, Arthur Rudolph, raised the issue again. He steered Seamans over to a corner where a model of the Saturn V was standing next to a model of the Minuteman on the same scale and discoursed on the comparative simplicity of solid-propellant rockets as opposed to the complexity of liquid chemical rockets the size of the Saturn V. His doubts about the all-up concept were implicit. He paused dramatically, turned to Seamans and said, “Now really, Bob!” Seamans got the point. “I see what you mean, Arthur,” he said. Encouraged, Rudolph buttonholed Mueller, drew him over to the same models and repeated his discourse about the relative merits and disadvantages of each. Mueller was unimpressed. “So what?” he responded.¹⁰ The planning for the all-up flight of AS-501 continued. In the spring of 1964, following a visit to Marshall, Dr. Golovin reported to General Sam Phillips at Headquarters that the all-up concept was being supported with enthusiasm by MSFC management.¹¹

AS-501: GETTING TO THE LAUNCH ON TIME

From the time of Mueller’s all-up teletype of 1 November 1963, it was four years, one week, and one day until the launch of AS-501. The interim was filled with exhaustive research and development of Saturn V systems, subsystems, and components. At Kennedy Space Center, a parallel effort involved the construction and verification of Launch Complex 39. Prior to the arrival of the AS-501 vehicle, the facilities had received a comprehensive checkout using an interim Saturn V facilities

STAGES TO SATURN

test vehicle, called 500-F. Saturn 500-F was rolled out on 25 May 1966, followed by exhaustive testing and development of procedures at Cape Kennedy.¹²

This preliminary experience provided invaluable information prior to the first operational launch of AS-501. Nevertheless, NASA management realized that the launch of the live vehicle would provide significant additional information for future Saturn V operations. For AS-501, therefore, additional plans were made for extraordinarily detailed experience reports. According to the instructions issued by General Phillips,

It is important that accurate, comprehensive records are obtained of failure, delays, holds, and scrubs for each pre-launch test and launch attempt on flight hardware, GSE [ground-support equipment], software, launch instrumentation, facilities, control centers, or MSFN [Manned Space Flight Network] which are involved in the final countdown from T-4 days to T-0. Data should be recorded for all failures, delays, holds and scrubs even though the time sequence or length of the pre-launch test in process at the time of the failure may not have been affected.¹³

In the meantime, Saturn V stages began arriving at KSC. All did not go well. Problems with hardware caused considerable delays and postponement of the launch date. In March 1967, an agenda for a briefing on AS-501, to be attended by General Phillips, included mention of 1200 problems resulting in 32 discrepancy reports. The memo to Phillips indicated that work teams had divided the problems into four separate categories and planned to work them off at an intensive rate of 80 per day. A typical problem was the discovery of an errant bolt in one of the F-1 engines and the requirement to see how it got there to make sure that nothing similar would happen again.¹⁴ Then in June 1967, after the AS-501 vehicle had already been stacked, it was necessary to take it down. On the West Coast, North American Rockwell had discovered some 80 weld flaws in the S-II second stage, designated S-II-6; it developed that S-II-1, already sitting in the AS-501 stack, had similar flaws. This costly delay nearly escalated when Boeing decided to follow up on its own stage, the S-IC, and discovered similar difficulties. Subsequent tests gave the S-IC-1 a clean bill of health, but not without a flurry of concern for the status of AS-501. Late in the month, NASA Headquarters issued a special directive calling for better management of the hardware changes on the AS-501 vehicle. In an attempt to keep the launch schedule on an even track, the teletype message warned, "It is essential that change traffic of all types be reduced to only those changes which are mandatory for safety or mission success."¹⁵ Finally, having overcome these and other numerous difficulties, AS-501 was "rolled out" on 26 August 1967.¹⁶

The teething troubles of AS-501 were not over, however, even after the vehicle reached the launch pad. Numerous preliminary test operations exposed a host of potential complications.¹⁷

The countdown demonstration test (CDDT) on AS-501 brought out additional difficulties which, as Program Manager Rudolph admitted, "caused numerous holds, delays, crew fatigue, scrubs, and recycles." Three recycles were required and instead of about one week, three weeks were needed to complete the test. Everything, Rudolph said, encountered difficulties—the Saturn V, the spacecraft, the launch facility, everything. Rudolph contended, however, that he was not surprised. It was, after all, the first time that a multitude of components were integrated into a "super system." On the first stage, for example, a number of the propellant valves opened simultaneously instead of in sequence as had been intended. On the second stage, items within the S-II were damaged by filling the LOX tanks too rapidly. In the third stage, cable connections were shorted as a result of the accumulation of moisture in the environment of the launch site. The instrument unit had difficulty in the environmental control system designed to keep the electronics in black boxes cool during operation of the vehicle. In the ground support equipment, a malfunction prevented proper pressure in the helium bottles, and the ground computer's problems included "intermittent operation due to design deficiencies, loose connections, electronic component failures, and insufficient maintenance."¹⁸

International prestige, as well as millions of dollars, were riding on the mission of AS-501. At NASA Headquarters, the Public Affairs Office was apparently feeling increasingly uncomfortable about questions from the press concerning the condition of AS-501. Would it ever fly, or not? Late in October, the head of the Public Affairs Office, Julian Scheer, met with Administrator Webb and representatives of the Office of Manned Space Flight in a heated conference that ended with Webb announcing that when he wanted the launch date announced, Webb would say so.¹⁹ Finally, the date was set for 7 November 1967. Then, less than a week before liftoff, on 2 November, MSFC started worrying about leaks in the seal rings of LOX fill and drain valves caused by aging of the Teflon over the long time that AS-501 had been on the launch pad. Concern was expressed about the batteries of the S-II stage for the same reason. Although these and other problems were subsequently solved, it put the count approximately 40 hours behind the detailed work plan leading to a launch on 7 November. General Phillips resolutely rescheduled the launch of Apollo 4 to 9 November at 7 a.m. EST.²⁰

Summing up the troublesome and erratic prelaunch experience with AS-501, Rudolph ticked off the lessons learned. The prolonged holds and recycling of the count wore out critical components with short lifetimes. For this reason, continuously updated logistical plans had to be prepared. Rudolph asserted that production components in many cases did not live up to the standards attributed to them by the qualification test program. He warned that the suppliers had to maintain much stricter

STAGES TO SATURN

manufacturing control and quality control to prevent degradation of such equipment. A number of problems resulted from the first-time conditions at Cape Kennedy. Work crews had to redesign many items "on the spot" while constrained by complicated procedural changes under pressure of the countdown. To launch successfully, concluded Rudolph, it was necessary to plan built-in holds, not only to replace components but also to prevent fatigue of the crews.²¹

These behind-the-scenes struggles heightened the drama of the launch of Apollo 4; the media, in the meantime, were attempting to convey to the American public something of the complexities of the Saturn V vehicle. Trying to find familiar examples with which to compare the Saturn V, the press corps and public relations offices came up with mountains of Saturn esoterica.

Because of its size and astronomical statistics, the F-1 engine received a good deal of mention in the press. The engine burned 145 000 liters (40 000 gallons) of propellant per minute, the equivalent of three metric tons of propellant per second. The cluster of five F-1 engines, which put out 33.4 million newtons (7.5 million pounds) of thrust, performed their operation for only 150 seconds, although each of the engines was tested for an average of 650 seconds of static firing before a launch. NASA also figured in a lifetime factor of 1400 seconds as a confidence factor for each engine. The only limiting factor was therefore the amount of propellant that could be crammed into the S-IC first stage.

The first stage boasted its own set of gargantuan statistics. Its girth was ample enough to allow three big moving vans to drive, side by side, into the first stage tank. The LOX tank of the first stage held enough liquid oxygen to fill at least 34 railroad tank cars (or 54, depending on which handout was read). To get the fuel from the tanks to the engines, the pumps on the S-IC first stage worked with the force of 30 diesel locomotives, and some of the fuel lines and associated valves were big enough for a man to crawl through. Fully fueled and running, the S-IC first stage turned out the equivalent of 119 million kilowatts (160 million horsepower)—twice as much power as all the rivers and streams of America running through hydroelectric turbines at the same time.

In trying to visualize the size of the Saturn V rocket, writers most frequently compared it in height to a 36-story building, or noted that it towered well above the Statue of Liberty, and weighed 13 times as much. A public relations pamphlet issued by North American Rockwell included the information that "6 200 000 lbs. is over 3000 tons; a good-sized Navy destroyer is only 2200 tons. Which gives you a fair idea of how much weight will have to be lifted off the ground before the Apollo spacecraft can be boosted into orbit, then shot almost 11 400 statute miles out into space and intricately maneuvered during the Apollo 4 flight." In terms of space payload capability, a writer for *Fortune* magazine pointed out that the Saturn V could lift "1500 Sputniks on a single launch, or

9000 copies of Explorer I, this country's first satellite, or 42 manned Gemini spacecraft."

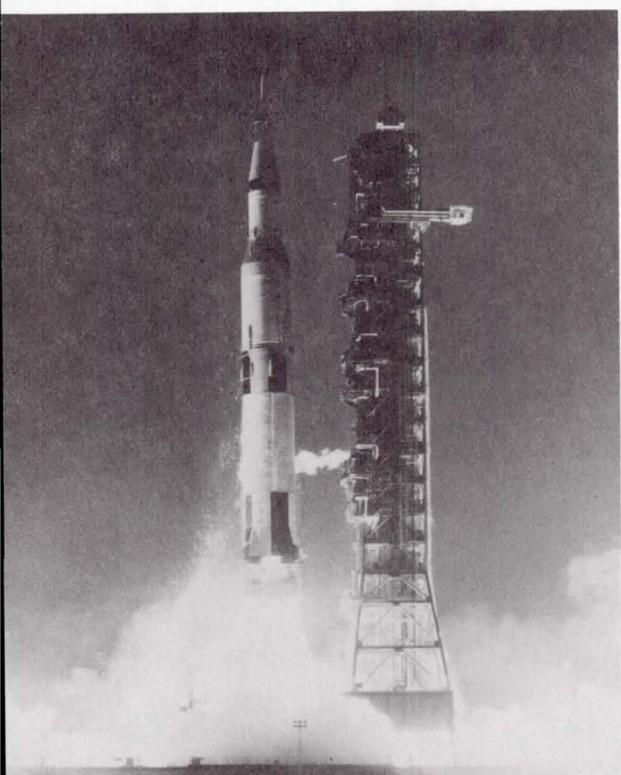
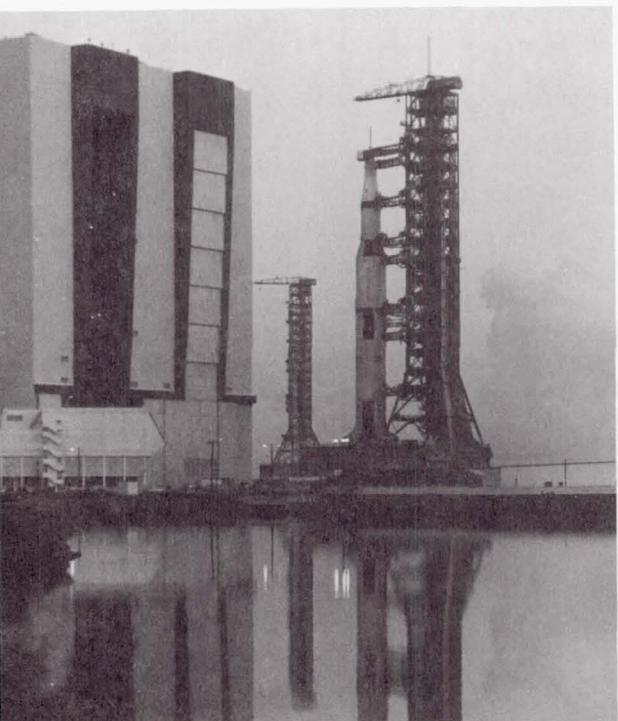
To make the most of the first Saturn V flight, data collection was also geared up to astronomical capabilities. During the Mercury test program, for example, data were received on the ground at a rate that would fill a standard printed page every second. The Apollo-Saturn vehicle was designed to relay some 300 pages of data in one second. The research, design, manufacturing, test, and preparation leading to the moment when the rocket was poised for its leap into space had required the services of over 300 000 scientists, engineers, technicians, and craftsmen, representing over 20 000 companies. The estimated cost for the AS-501 vehicle was \$135 million for the rocket and \$45 million for the spacecraft.²²

AS-501: MISSION ACCOMPLISHED

The enormity of the effort involved in the Apollo-Saturn program and the trials and tribulations of getting the AS-501 countdown to work provided an additional dramatic background for the final preparations. The inherent risks of the all-up concept seemed to multiply the chances for total failure. The electric tension of the atmosphere heightened perceptibly with the influx of VIPs. Congressional figures, the diplomatic corps and other foreign visitors, industry executives, and NASA managers began arriving at the Cape. Late in the afternoon of 6 November, von Braun left Huntsville in NASA's Gulfstream No. 3. After arrival at Patrick Air Force Base, von Braun was scheduled for an exclusive executive dinner and conference. The next day, Tuesday, 7 November, included further executive sessions with the Office of Manned Space Flight and other contractor personnel. Early in the morning of 8 November 1967, the final 24-hour countdown period for AS-501 began. The day included a major press conference at the Vertical Assembly Building, and, late in the evening, a dinner for top-level NASA personnel and industry representatives.

At dusk on 8 November, the silhouette of AS-501 faded with the setting sun, but as darkness descended over the Atlantic, Apollo 4 reappeared as a shining white pillar swathed in floodlights on Pad 39. The towering vehicle made a dramatic focal point for the pressures that mounted during the night. The count continued through programmed holds, then through a spate of minor difficulties as the clocks ticked away the minutes and seconds to the scheduled launch time, seven o'clock in the morning of 9 November.

At only one second past the appointed hour, the Saturn V lifted off the pad, its engine exhaust emitting plumes of stabbing red fire, lighting up the low-lying Cape landscape—an exceedingly dramatic scene in the



Top left, the first flight-ready Saturn V, AS-501, is rolled out of the Vehicle Assembly Building at KSC on 20 August 1967. Above, the AS-501 stands for weeks on the pad at Launch Complex 39, bedeviled by minor problems. Then (left) on 9 November 1967, it lifts off to a perfect flight; the "all-up" concept has been vindicated.

half-light of dawn. The spectacular flames, billowing exhaust clouds, and the rolling thunder of the engines stunned the onlookers. Dr. William Donn, of Columbia University's Lamont Geological Observatory, at Palisades, New York, reported that the only man-made sounds that exceeded the liftoff noise of the Saturn V were nuclear explosions and added that the only natural sound on record that exceeded the noise of the Saturn V engines was the fall of the Great Siberian Meteorite in 1883. Five and a half kilometers away, in the studio trailer of the Columbia Broadcasting System, the commentary of CBS correspondent Walter Cronkite was all but drowned out by the thunder of Saturn's engines, and Cronkite himself was subjected to a shower of debris shaken loose from the walls and ceiling of his broadcasting booth.²³

The all-up concept was undeniably successful. With AS-501 up, von Braun could finally admit his lingering doubts about it. He turned to Rudolph in the firing room at Kennedy Space Center, and told him that he thought such a completely flawless three-stage flight would never have been possible on the first try.²⁴ During a postlaunch press conference von Braun said, "No single event since the formation of the Marshall Center in 1960 equals today's launch in significance [and] I regard this happy day as one of the three or four highlights of my professional life—to be surpassed only by the manned lunar landing."²⁵

The flight of *Apollo 4* was a success on all accounts. In W. C. Schneider's first teletyped 24-hour report, the opening sentence told the story: "The *Apollo 4* mission was successfully accomplished on 9 November 1967." Talking to reporters later, he called AS-501 a bench mark to aim for in succeeding flights. *Apollo 4* would be "a tough act to follow."²⁶

The flight marked the initial flight testing of the S-IC and S-II stages; the S-IVB was essentially the same as that used in the Saturn IB launches. The first-stage S-IC performed with the accuracy anticipated by launch officials. A timer cut off the center F-1 engine at 135.5 seconds into the flight, and the outboard engines cut off at LOX depletion in 150.8 seconds, when the vehicle had recorded 9660 kilometers per hour at an altitude of 61.6 kilometers. The separation of the first stage took place only 1.2 seconds off the predicted time lines, and the cameras aboard the S-II showed a clean separation of the stages. Other major systems of the S-IC, including the pneumatic control pressure system, pressurization, and propellant utilization, performed within acceptable ranges. On the S-II second stage, the cluster of five J-2 liquid-hydrogen engines achieved perfect sequencing for engine start and burn. Two slight variations were observed by ground controllers: engine-start bottle pressures were somewhat higher than predicted, and the temperatures of the thrust chamber jackets increased at rates higher than predicted. Neither of these minor anomalies exceeded the operational limits of the Saturn V; all other systems performed normally. Cutoff for the S-II occurred at 519.8 seconds, about 3.5 seconds later than indicated on the

STAGES TO SATURN

mission control sheets. The troublesome external insulation on the liquid-hydrogen tank of the S-II stage survived the countdown and launch with no recorded failures.

Variations in the S-IVB third-stage performance were greater than those of the lower stages. In achieving orbit, the guidance control system ended the first third-stage burn a few seconds beyond the predicted shutdown point, when the stage achieved a speed exceeding 27 000 kilometers per hour at an altitude of 192 kilometers. Prior to the restart sequence, after two revolutions in Earth orbit, telemetry received at Cape Kennedy indicated that the liquid-hydrogen ullage pressure was somewhat below the anticipated minimum and that the status of the helium repressurization spheres was below normal for S-IVB restart preparations. Mission personnel decided that the engine could be reignited in spite of these deficiencies, and the third stage responded successfully. The instrument unit (IU) ended the second burn several seconds short of the expected duration, reacting to the earlier extended burn of the S-II stage, made at higher thrust levels of the J-2 five-engine cluster, which enabled the third stage to make its mission profile with less burn time required. The IU operated exceptionally well with only 40 questionable measurements and a single pair of confirmed failures out of about 2862 measurements made during the Saturn V portion of the mission.²⁷

Behind the primary mission objectives, NASA personnel closely monitored many individual items of flight hardware. Of singular importance was the experience of coordinating the platoons of NASA and contractor personnel during the long months of prelaunch operations. Even as the painstaking procedure of checking out each stage and every item in the stage progressed, launch engineers were evaluating the procedures themselves on this first Saturn V mission. The mobile launch concept was only one example. Planned and orchestrated to reduce the time the vehicle remained on the launch pad and exposed to the effects of corrosion, dust, and weather, the concept required that the Saturn V be assembled and checked out inside the huge VAB. With the huge vehicle complete, the plan called for mobility to reposition the complete vehicle on the launch pad, 5.5 kilometers distant. This meant the use of the crawler, bearing the combined launcher and vehicle out to the pad. The launch itself tested the holdown arms for the first time. Not only did the arms stabilize the vehicle during rollout to the pad and keep the vehicle in place during the long countdown, but they also held down the straining vehicle after ignition until computers verified satisfactory operation of the engines and signaled release of the rocket. The strain was so intense that the mobile launcher was actually stretched about 20 centimeters.

The mission also tested the gimbal capability of the engines. The vehicle had to make a roll maneuver around its vertical axis after launch and pitch into an inclined northeasterly trajectory after climbing away

from the launch pad. Before ignition of the J-2 engines of the second stage, mission personnel closely watched the second-stage ullage maneuver. Following separation of the first and second stages, the nearly weightless propellants tended to surge forward, climbing the propellant tank walls as acceleration decreased. Unless the propellants were settled once more against the propellant line inlets to the engines, no second-stage ignition could occur. So the eight ullage rockets had to fire first, accelerating the stage and forcing the propellants into place. The system worked, and the five J-2 engines burned as expected. The emergency launch escape tower jettisoned perfectly, and the third stage performed like the veteran it was. The IU for the Saturn V functioned just as planned, and reignition of the S-IVB third stage represented another crucial test: the second burn would supply the acceleration required for the translunar trajectory.

The S-IVB reignition had appeared to be a particularly difficult sequence. The behavior of hydrogen in orbit was a problem, and the restart sequence depended on especially designed, complex equipment. After its first burn, cutoff, and three-hour coast through space, the J-2 had to be reconditioned to cryogenic temperatures before the final restart sequence began. To purge the engine of contaminants remaining after the first burn, an automatic sequence initiated a helium purge, and a gaseous hydrogen start tank was refilled by a tap line from the stage's hydrogen tanks. Valves opened to permit liquid hydrogen and oxygen to trickle through the engine and cool down its parts to the requisite cryogenic temperatures. During an ullage maneuver to seat the propellants for entry into the pumps, an automatic sequence ran a final check on temperatures, pressure levels, and other engine conditions to verify the readiness of the engine and propellant systems. When the IU received positive indication on all the numerous readings required, it triggered the final start sequence for reignition. *Apollo 4* proved the restart capability, and the second burn put the spacecraft into a very high elliptical orbit, reaching more than 16 000 kilometers from Earth. With its mission complete, the S-IVB separated from the spacecraft, which performed its own programmed burns and maneuvers before CSM-CM separation and CM reentry.²⁸

Following the months of doubts and problems created by the rocky research and development of the S-II second stage, the disastrous fire at Cape Kennedy early in 1967, and the troublesome experiences with the countdown demonstration tests of the AS-501 vehicle late in 1967, the flawless mission of *Apollo 4* elated the entire NASA organization; everyone looked ahead with buoyant spirits. Returning to Huntsville, von Braun received a call from Brainerd Holmes on 15 November. "Congratulations! That was such a remarkable achievement with Saturn V. I was very excited about it," Brainerd exclaimed. Von Braun warmly responded that it showed the spacecraft to be in better shape than many

STAGES TO SATURN

people had thought following the fire and redesign and added that it performed magnificently during reentry.²⁹

NASA management shared its elation with the Apollo-Saturn contractors as well. In a letter to Bill Allen, president of the Boeing Company, George Mueller pointed with pleasure to the success of the all-up concept, and continued in glowing terms about the success of the industry-government team. The mission of *Apollo 4*, Mueller emphasized, was a true landmark, ". . . a very large step forward. It is, in my view, the most significant single milestone of the Apollo-Saturn program." Urging continued dedication to the task ahead, Mueller closed with the remark that it was possible to fulfill the national commitment of landing Americans on the moon and returning them safely to Earth within the decade.³⁰

In the meantime, planning continued for the flight of the second Saturn V mission, to be known as AS-502, or Apollo 6. In the aftermath of the AS-501 flight, NASA planners were optimistic in planning for the next two missions, both of which were to be unmanned. General Phillips advised NASA center directors that if AS-502 was successful, AS-503 would become the first Saturn V manned mission. Thus, AS-502 served as an all-important dress rehearsal for the first manned flight.³¹

THE TROUBLESOME BIRD: AS-502

The general euphoria was badly worn by the problem-prone mission of AS-502. Nothing had indicated the impending series of trials ahead. After a satisfactory countdown, AS-502 blasted off from Launch Complex 39 on schedule, early in the morning of 4 April 1968. The first thing to go awry was the S-IC first stage, which developed longitudinal oscillations of five cycles per second during the last moments of the first-stage burn. These oscillations, known as the "Pogo effect," had occurred on the first Saturn V, but their magnitude on AS-502 became alarming. "The second Saturn V's takeoff at the Cape was faultless," von Braun recalled. "For two minutes everything looked like a repeat of the first Saturn V's textbook performance. Then a feeling of apprehension rolled through the launch control center when, around the 125th second, telemetered signals from accelerometers indicated an apparently mild Pogo vibration." The lengthwise oscillation lasted less than 10 seconds.

After the moments of concern about the first-stage Pogo readings, launch personnel felt better about the stage separation and ignition of the five J-2 engines on the S-II second stage. After burning 4.5 minutes, however, the number two engine began to develop unwholesome problems. The engine began to falter; it lost thrust and then shut down. No more than a second later, the number three engine suddenly shut off as well. To compensate for the loss of 40 percent of its thrust, the IU steered

the faltering second stage into a recomputed trajectory to reach the programmed altitude for third-stage separation. After some overtime firing, the S-II finally shut down its three remaining engines and fell back from the S-IVB. The third stage fired up normally, and the S-IVB, IU, and payload finally made it into an Earth parking orbit, although a somewhat lopsided one. After two orbits, the bird received a command for the third stage to reignite. Nothing happened. The J-2 engine just would not restart, despite repeated efforts. Salvaging all that was available from the flight, mission controllers succeeded in separating the CSM from the malfunctioning third stage, got a couple of burns out of the service module engine to get the command module into better position for the reentry tests, and finally brought the CM through reentry and splashdown to verify the heat shield.

"Had the flight been manned, the astronauts would have returned safely," von Braun emphasized afterward, "but the flight clearly left a lot to be desired. With three engines out, we just cannot go to the Moon."

In the aftermath of the marginal flight of AS-502, teams went to work to find answers to the problems. Pogo had been encountered previously in Titan-Gemini and other launch vehicles, and a fix was likely in the future. However, the J-2 engine failures involved a problem of unknown origins and causes, indicating the need for some intensive sleuthing.

Armed with reams of reports and telemetry data from the AS-502 flight, the J-2 problem team assembled, including engineers from MSFC and Rocketdyne. The record of temperature readings from thermocouples in the S-II tail section provided the tipoff, beginning at the 70th second of flight, when investigators discovered telltale indications of a flow of cold gas. Such a phenomenon could only come from a leak of liquid-hydrogen fuel, and the leak was located in the upper regions of the number two engine. Even more conclusive was the coincidence of increased cold flow from about the 110th second on, when ground controllers first noticed the falter of thrust. Clinching the theory of a fuel leak, the J-2 team found indication that a split second before the number two engine shut down, hot gas had erupted in the area of the leak. The only theory to explain a hot gas eruption, followed by engine shutdown, was the failure of the J-2 igniter line in the upper part of the engine.

These data allowed the J-2 group to reconstruct the sequence of the failure. The leaking fuel line, leading to the igniter, sprayed the upper engine section with liquid hydrogen, even though some fuel continued through the line and the engine kept burning. Finally, the line broke completely, and fiery, high-pressure gas from the combustion chamber backed up and spurted through the rupture. Combustion chamber pressure began to fall off, so that the low-thrust sensing equipment triggered a sequence to shut down the engine by closing the fuel and oxidizer valves. The electrical sequence to close number two LOX valve

STAGES TO SATURN

went erroneously to number three. Closing the fuel valve for engine number two and the LOX valve for engine number three shut down both engines. Telemetry from the J-2 engine on the third stage told the same story as engine number two of the second stage: a failed igniter line. The S-IVB had arrived in orbit before the failure was complete, but could not restart the engine.

The MSFC and Rocketdyne investigation team now knew how the engines and igniter fuel lines failed, but no one could say why. Engineers set up special test stands to wring out the fuel lines again. The tests began by subjecting the igniter fuel lines to successively higher pressures, flow rates, and vibration, surpassing the extremes that might reasonably be encountered during a mission. The lines survived the punishment. Next, the investigators checked into the possibility of resonance failures, concentrating on the bellows sections in the lines. The accordionlike sections, located near either end of the line, were intended to provide flexibility for expansion and contraction, and engineers wondered if some flow rates could induce "buzzing" in the bellows—a phenomenon that, if sufficiently severe, could cause metal fatigue and failure. There was buzzing, but the lines held. Finally, Rocketdyne technicians decided to test the lines in a vacuum chamber, in close simulation of the environment where failure occurred. Eight lines were set up for test in a vacuum chamber, and engineers began to pump liquid hydrogen through them at operational rates and pressures. Before 100 seconds elapsed, each of the eight lines broke; each time, the failure occurred in one of the bellows sections. By using motion picture coverage acquired during repeated vacuum chamber tests, Rocketdyne finally could explain the failures.

The igniter fuel lines were installed on the engine with protective metal braid around the bellows section. When tested in a chamber that was not in a vacuum condition, the surrounding air was liquefied by the extremely cold liquid hydrogen flowing through the lines and was trapped between the bellows and the protective metal braid. This condition damped subsequent vibration in the fuel line. When tested in the vacuum chamber, where the environment simulated the conditions of space, there was no liquefied air to dampen the destructive resonance. A redesigned igniter fuel line eliminated the bellows sections, replacing them with bends in the line to allow for expansion and contraction during the mission.

Concurrent with the J-2 failure investigation, a Pogo task force, with representatives from MSFC and other NASA agencies, the contractors, industry, and universities, analyzed the first-stage F-1 engines and the overall Saturn V vehicle. The Pogo phenomenon, they reported, originated from two sources. While F-1 engines burned, the thrust chamber and combustion chamber of each engine developed a natural vibration of some 5.5 hertz. Further, the whole vehicle vibrated in flight with a

varying frequency that peaked at 5.25 hertz around 125 seconds into the flight. When the engine frequency closely matched the structural frequency, Pogo vibrations appeared up and down the entire vehicle. The vibration was not in itself destructive, but it did increase the stresses on the vehicle and the astronaut crew, because the lighter spacecraft, perched at the tip of the tall rocket, was buffeted more than the engines at the bottom. The team investigating Pogo concluded that they should "detune" the engine frequencies away from those of the structural frequencies.

The group explored a number of possible fixes before settling on pneumatic "shock absorbers" in the LOX lines leading to each of the five F-1 engines in the first stage. The so-called shock absorbers made use of cavities in the LOX line prevalve assembly. The prevalve assembly contained a bulging casting in the LOX line to accommodate the movement of a big valve that opened or closed the LOX line. During engine operation, with the valve in the open position, liquid oxygen filled the casting's cavity to about half its volume. Engineers tapped the first stage's ample helium supply (used to pressurize the fuel tank), and filled the remainder of the valve cavity with helium gas. The helium gas in the cavity acted as a shock absorber by damping the engine pulsations into the LOX lines and into the vehicle structure.

At Mississippi Test Facility, engineers successfully demonstrated the two fixes during August 1968, with test firing of the S-IC first stage equipped with the Pogo suppression equipment on the F-1 engines, and the S-II second stage with the redesigned igniter fuel lines on the J-2 engines. The demonstration cleared the way for a manned launch of AS-503, as Apollo 8. The AS-503 was planned to place the manned CSM in a low Earth orbit. If the interim Apollo 7 mission, boosted by a Saturn IB, verified the redesigned CSM and its new safety features, then the Saturn V-Apollo 8 mission could be revised boldly. "There is even a remote possibility of a spectacular swing around the Moon by the manned spacecraft," von Braun said in the autumn, a little over a month before the scheduled launch. "That a mission as bold as the last is even considered, for the first Saturn V to be manned, bespeaks planners' confidence that all about it has been set aright."³²

REACHING THE PINNACLE: AS-503 THROUGH AS-506

In many respects, the momentous mission of *Apollo 11* in 1969, which put Armstrong, Aldrin, and Collins on their way to the first manned landing on the moon, has obscured the importance of the first manned Apollo-Saturn mission, that of Apollo 8, or AS-503. The decision to man AS-503 was a significant step forward, in some respects

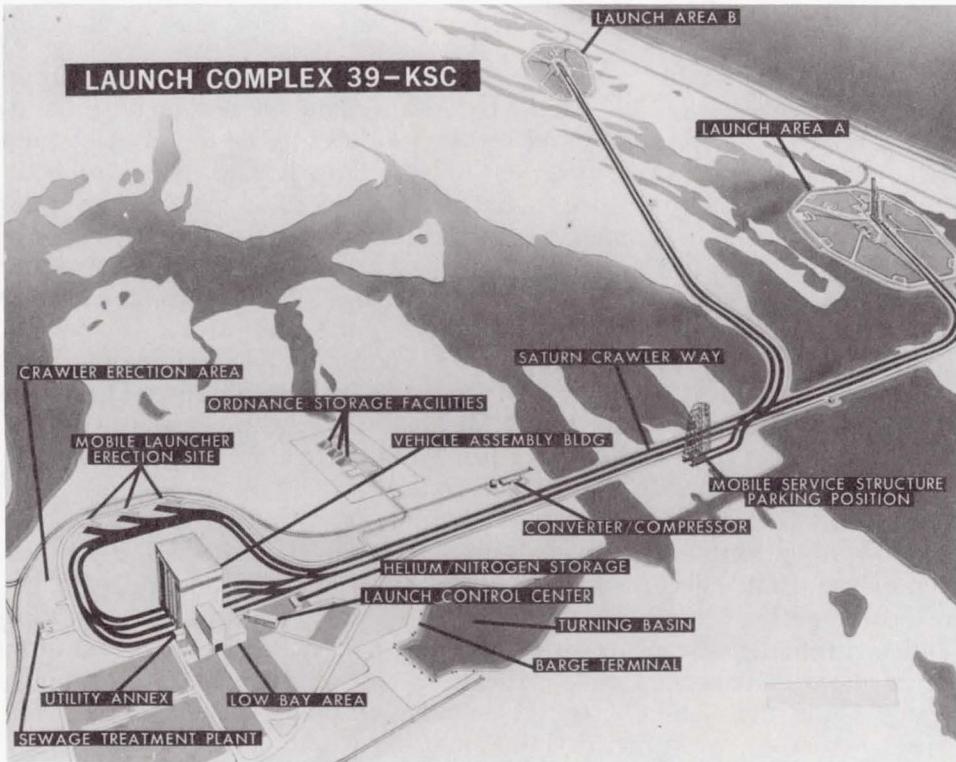
STAGES TO SATURN

comparable to the decision to make AS-501 the first all-up configuration. The decision to send it around the moon was even more significant.

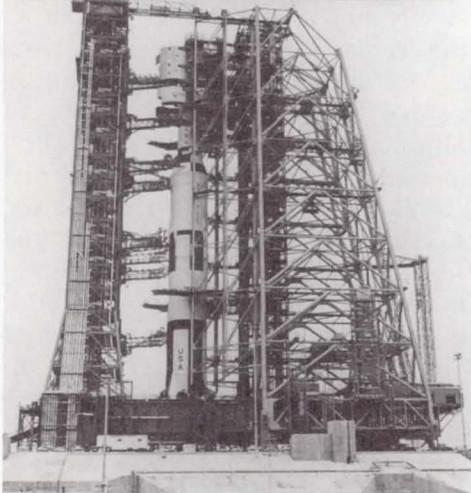
Back in June 1967, a NASA memorandum was issued warning against the tendency by NASA employees and others "to create overly optimistic impressions of NASA's capability for early achievement of such key milestones as Apollo long duration manned missions, manned Saturn V missions, and the lunar landing mission." The memorandum observed that AS-503 had a low probability of being the first Saturn V manned mission and that even AS-504 had only a moderate probability of being manned.³³ If AS-504 were manned, it would be a low-Earth-orbit flight. At the same time, some executives at NASA Headquarters were suggesting the possibility of at least a lunar orbital manned mission by the third manned Saturn V.³⁴ By September 1967, Robert R. Gilruth at Houston was advocating "four, or perhaps even five, basic manned mission types . . . before lunar landing capability is achieved. One of these mission types is a lunar orbit mission." At the same time, Gilruth strongly advocated a third unmanned launch of the Saturn V vehicle to "help assure launch vehicle maturity prior to manning." Gilruth noted that "the probability of landing on the moon before 1970 is not high."³⁵

The manning of AS-503 became an even more touchy question following the difficulties of AS-502 in the spring of 1968. A prerequisite to a manned mission for 503 was a design certification review, but as von Braun pointed out to Mueller, too many people at Marshall were still working on the data received from the troublesome AS-502 mission. Mueller was anxious to get a commitment before he appeared before Congress on 23 April to testify on NASA plans, but von Braun pleaded for more time—two or three weeks. Mueller finally agreed.³⁶ On 24 April, Phillips said that he was recommending preparation of AS-503 for manned flight with an option to revert to the unmanned configuration if necessary. However, difficulties uncovered by AS-502 continued to plague the question of a manned or unmanned mission on AS-503. On 29 April, Arthur Rudolph, the manager of the Saturn V Program Office, advised Phillips that the continuing problems with AS-502 anomalies still did not allow him to make a firm recommendation for a Saturn V payload of 45 000 kilograms or more, which Phillips had requested by 30 April 1968.³⁷ Nevertheless, preparations for launching AS-503 either in the manned or the unmanned configuration necessarily continued.³⁸

NASA planners had wanted to use AS-503 to fly the complete Apollo-Saturn configured for the lunar landing mission. This plan presumed an Earth-orbital flight, testing both the command module and the lunar module in the flight mode and using them both to perform maneuvers that would simulate the operations in the lunar environment as closely as possible. During late spring and early summer of 1968, work on the lunar module fell behind. By August, General Phillips glumly concluded that the original mission for AS-503 could not be flown until



**MOBILE SERVICE STRUCTURES ON PAD 39A
WITH SATURN V ON MOBILE LAUNCHER-KSC**



early 1969. With only 18 months to get to the moon before the decade ended, the schedule slippage of Apollo 8 was extremely serious.

But George Low, the spacecraft manager at Houston, came up with what Phillips called a "daring idea." Low proposed to skip the Earth-

STAGES TO SATURN

orbital test phase and postpone lunar module trials until the next Apollo-Saturn after AS-503. In the meantime, Low argued, go ahead and send a crew in the command and service modules to the moon. After all, the spacecraft hardware assigned to the launch had been built to specifications for actual mission hardware. Use it. A hastily convened session of the Apollo management team brought key people flying into Marshall Space Flight Center, centrally located to the other major Apollo operations at Headquarters, KSC, and Houston. The preliminary three-hour session ended on a distinctly up-beat note. More study was required, but a circumlunar flight for Apollo 8 looked quite feasible. Back in Washington, Phillips explained the plan to Thomas O. Paine, Acting Administrator while James Webb was attending a space conference in Vienna. Paine was not so sure. "We'll have a hell of a time selling it to Mueller and Webb," he warned Phillips.³⁹

Not until early fall were NASA planners ready to decide on manning AS-503 or to confirm the prospects of a lunar orbital mission. On 19 September 1968, the Office of Manned Space Flight made an intensive review of each problem uncovered by AS-502, examining the solutions and scrutinizing test procedures and results. In a long memorandum reviewing these aspects, George Mueller recommended to Acting Administrator Paine that AS-503 should be manned. On 11 November 1968, Mueller further recommended to Paine that AS-503 also circumnavigate the moon. Paine's reply to Mueller on 18 November 1968 made it official: AS-503 would leave the lunar module behind, but go for a manned lunar orbit.⁴⁰

Nobody wanted a repeat of the worrisome AS-502 mission, and so the Apollo 8 launch vehicle received an exceedingly thorough going over before launch day. Several months before the scheduled launch, even before the official decision to man AS-503, Dieter Grau, Chief of Marshall's Quality and Reliability Operations, sat through a two-day meeting when all the major contractors discussed the action items for Apollo 8/AS-503. The participants seemed to be approaching a consensus that the vehicle was ready to go. Having lived and worked closely with the vehicle and its various components for months, however, Grau did not have a good feeling in his bones that all was well. In the face of the growing consensus, Grau took a position of caution. As Grau recalled, von Braun sensed his reticence and asked what more should be done. Grau wanted the opportunity to do one more complete check and von Braun gave it to him. Personnel in Grau's laboratories went over the AS-503 vehicle again, rechecking subsystems, interfaces, and drawings to make sure everything was all right. Sure enough, numerous little mistakes and potential problems were uncovered. "We went through the vehicle from top to bottom," Grau said. "I think that was kind of a life saver. We found so many things which needed to be corrected and improved." After these extra weeks of checking and rechecking, Grau

THE GIANT LEAP

and his people in the Quality and Reliability Laboratory finally gave the green light for the launch of Apollo 8.⁴¹

"Wet" and "dry" countdown demonstration tests began for AS-503 on 5 December 1968, and concluded by 11 December, clearing the way for the final countdown for launch, which began four days later. As the launch countdown proceeded, the final Pogo suppression test took place on the S-IC-8 stage at Mississippi Test Facility during a 125-second static-firing test on 18 December. On the same day, MSFC engineers finished a series of tests on the S-IVB battleship unit to verify the redesigned fuel lines. The program included three hot tests, from 4 December to 14 December, ranging from about 122 seconds to 435 seconds. The last of the miscellaneous component tests was completed on 18 December, with Apollo 8 poised on its pad, only three days away from launch.

For the premier launch of a manned Saturn V, NASA prepared a special VIP list. The fortunate individuals on the list received an invitation in attractively engraved and ornate script: "You are cordially invited to attend the departure of the United States Spaceship Apollo VIII on its voyage around the moon departing from Launch Complex 39A, Kennedy Space Center, with the launch window commencing at 7 A.M. on December 21, 1968." The formal card was signed "The Apollo VIII Crew" and included the notation, "RSVP."

With the primary objectives to verify the manned spacecraft, support systems, and lunar orbit rendezvous procedures, *Apollo 8* lifted off from KSC at 7:51 a.m. EST, on 21 December, 1968, crewed by Frank Borman, commander; James A. Lovell, Jr., command module pilot; and William A. Anders, lunar module pilot. In contrast to its predecessor, AS-503 performed without a hitch. The telemetry readings from the S-IC indicated that the Pogo suppression system worked as planned, and no longitudinal vibrations were reported. Staging of the first and second stages went smoothly, followed by the staging of the S-II and S-IVB near the top of the launch trajectory. The S-IVB, IU, and spacecraft went into Earth parking orbit 11.5 minutes after launch. During the second orbit, the S-IVB stage reignited, boosting the vehicle into translunar trajectory at over 38 600 kilometers per hour. After separation of the spacecraft,

Apollo 8 S-IVB stage is left behind at 50 000 kilometers venting its remaining fuel while the CSM is on its way to man's first escape from Earth's gravity and orbit of the moon.



STAGES TO SATURN

the spent third stage was directed into a trajectory for solar orbit and Saturn V's job was done. At 3:29 p.m. EST, on Monday, 23 December 1968, *Apollo 8* crossed the dividing line that separates the Earth's gravitational sphere of influence from that of the moon, propelling men beyond control by Earth for the first time in history.

On Christmas Eve, *Apollo 8* slipped behind the moon, and the three crewmen became the first to see the far side. The last TV transmissions of the day were verses from the first chapter of Genesis, read by the astronauts. From earlier transmissions, the vivid image of the emerald, brown, and cloud-wreathed Earth-rise above the barren gray surface of the moon gave the broadcast unusual drama. Some 400 000 kilometers away in space, the passengers in *Apollo 8* beamed a special message: "Good night, good luck, a Merry Christmas and God bless all of you—all of you on the good Earth." On Christmas Day, the spacecraft's main engine fired a three-minute burst to push *Apollo 8* out of lunar orbit and into trajectory for return to Earth. Swaying under its parachutes, the command module carrying the three crewmen settled safely into the Pacific late in the morning of 27 December.⁴²

A preliminary review of AS-503 data confirmed the faultless performance of the Saturn V launch vehicle. The fix for Pogo problems had worked; the J-2 engines of the S-II and S-IVB stages had worked; the modified igniter lines had worked. The Saturn V was in good shape for the next two flights leading up to "the big one"—the moon landing, less than seven months away.

As the next Saturn V in the series, the AS-504 vehicle for Apollo 9 comprised the first complete Apollo-Saturn configuration, with the lunar module aboard. Manned by astronauts James A. McDivitt, David R. Scott, and Russell L. Schweickart, *Apollo 9* rose from KSC's Launch Complex 39A on 3 March 1969, for a low-Earth-orbit flight to check out docking of the CSM and LM in space. After the launch had been postponed for three days because of minor illness among the crew, the mission proceeded smoothly. All launch vehicle stages performed normally, with S-IVB reignition taking place after the CSM-LM docking maneuver and removal of the LM from the spacecraft-lunar-module adapter (SLA). With the S-IVB in an Earth-escape trajectory, mission control officials were unable to perform third-stage propellant dumps. The remainder of the mission proceeded with great success, including firing of the LM engines for descent and ascent maneuvers, transfer of two of the crew (McDivitt and Schweickart) to the LM and back again, a "space walk" by Schweickart, and splashdown on 13 March.

Apollo 10, launched on 18 May 1969, again carried the full Apollo-Saturn configuration with the Saturn V launch vehicle AS-505. After the second burn of the S-IVB to place the S-IVB, IU, and spacecraft into translunar trajectory, T. P. Stafford, J. W. Young, and E. A. Cernan completed the docking maneuver, shown live on commercial television for

the first time. The third-stage propellant dump came off normally, and the S-IVB went into an Earth-escape trajectory. The spacecraft continued toward the moon and entered into a low, circular lunar orbit. Stafford and Cernan undocked the LM and flew even closer to the lunar surface, testing the descent stage, which was jettisoned before the ascent stage rendezvoused with the CSM. The mission demonstrated the lunar orbit rendezvous technique and verified LM operations in the lunar environment, along with Apollo mission guidance, control, radar, TV transmission, and other mission systems. The crew completed the eight-day flight with splashdown in the mid-Pacific on 26 May 1969.⁴³

Meanwhile, the Saturn V vehicle AS-506 neared its special date in history, when Apollo 11 lifted off to carry three astronauts to a landing on the moon.

By the time of Apollo 11 (AS-506), the Saturn V launch vehicle had been considerably eclipsed in the public eye. Although television coverage and still photography inevitably portrayed the towering white rocket, the attention of the press and public was primarily fastened on the crew itself. Commander Neil A. Armstrong, command module pilot Michael Collins, and lunar module pilot Edwin E. Aldrin, Jr., spent the last few days prior to the flight in the fish bowl of public attention. It was symptomatic that the standard chronology of such aerospace events, *Astronautics and Aeronautics*, 1969, in recapitulating the mission of *Apollo 11*, devoted only a few lines to the Saturn V launch vehicle. The stars of the show were the crew, the spacecraft, and the spiderlike lunar module to land Armstrong and Aldrin on the surface of the moon. Understandably, the crew members themselves gave most of their thought and attention to the details of the spacecraft and the details of the lunar mission, leaving the care and feeding of the launch vehicle to the technicians from Marshall and their contractors.

This is not to say that the astronauts had no thoughts whatsoever about the vehicle. Early on the morning of 16 July 1969, riding in the van on the way to the launch pad, Michael Collins was struck again by the enormity of the vehicle that was to carry them aloft:

Last night the Saturn V looked very graceful, suspended by a cross fire of search lights which made it sparkle like a delicate opal and silver necklace against the black sky. Today it is a machine again solid and businesslike, and *big*. Over three times as tall as a Gemini-Titan, taller than a football field set on end, as tall as the tallest redwood, it is truly a monster.⁴⁴

AS-506 lifted off at 9:32 a.m. EDT, 16 July 1969. The number of observers around the launch site was conservatively estimated at a million, including 200 congressmen, 60 ambassadors, 19 governors, 40 mayors, and other public figures. Vice-President Spiro T. Agnew and former President and Mrs. Lyndon B. Johnson were there. Live television coverage of the liftoff was beamed to 33 countries on six continents

STAGES TO SATURN

and watched by an estimated 25 million TV viewers in the United States alone. Radio commentary was heard by additional millions around the world.⁴⁵

Inside the spacecraft, Collins was very much aware of the gimbaling of the F-1 engines below, separated from the command module by the length of a football field. Watching prior Saturn launches, he had been impressed by the rigid and stately progress of the rocket off the pad. From the inside, the ride was jiggly and caused a kind of twittering feeling because of the gimbaling engines. There was not as much noise as Collins had expected, although it probably would have been difficult to communicate without the intercom. The Saturn ride, he reported, was a bit softer than the ride he had experienced in the Titan-Gemini launches. During the boost phase, the crew watched the gimbaling rates of the F-1 engines to make sure that no dangerous deviations from the course occurred, the flow rates of the propellants, and the thrust levels of the rocket engines. The first 10 seconds of the liftoff concerned the astronauts somewhat because the Saturn V rose so close to the umbilical tower. After that point, the crew relaxed a bit, and the noise and motion of the rapidly climbing rocket abated. Collins noted to himself that all the lights and dials indicated no problems. "All three of us are very quiet—none of us seems to feel any jubilation at having left the earth, only a heightened awareness of what lies ahead."⁴⁶

During the long months of astronaut training, the emphasis had been on operations and control of the spacecraft. It had not been necessary for the crew members to become experts on each of the booster stages. Still, because the Saturn V was going to be the prime mover of the mission, the crew picked up odds and ends of information and formed an opinion about it.

As far as Collins was concerned, the Saturn V vehicle itself had been the largest question mark in the Apollo-Saturn program. If there had been trouble with the command module or with the lunar excursion module, it would have been possible to have found a fix on it in a matter of months. If one of the huge, complex, Saturn V's had blown up, however, during one of the R&D launches, for example, then several years would have been required to have made a fix. According to Collins, "the Saturn V loomed in our minds as being the biggest single unknown factor in the whole lunar landing program." Now, as the *Apollo 11* vehicle soared upward, consuming tons of propellants in the S-IC booster, the next concern was the S-II boost phase. "Staging, it is called, and it's always a bit of a shock, as one set of engines shuts down and another five spring into action in their place," Collins explained. "We are jerked forward against our straps, then lowered gently again as the second stage begins its journey. This is the stage which whisperers have told us to distrust, the stage of the brittle aluminum, but it seems to be holding together, and besides, it's smooth as glass, as quiet and serene as any rocket ride can

be." Although Collins and others had the feeling that the S-II was probably going to be the weakest link in the chain of the three stages of the Saturn V, Collins had been very much encouraged with the fervor of workers at North American Rockwell. He was impressed by their hard work and impressed by the way they caught up with the time lags in the S-II program. Still, all that talk about brittle aluminum and cracks in the S-II tankage left a few nagging thoughts. The S-II performed beautifully, however, leading up to the end of its boost phase and the staging of the S-IVB.

Nine minutes into the mission, the second stage shut down, and the crew waited, weightless, for the ignition and acceleration of the S-IVB third stage. Although third-stage ignition occurred on schedule, the momentary wait seemed interminable to the expectant astronauts. When the S-IVB ignited, the acceleration softly pushed the crew back into their contoured seats. The third stage, as Collins described it, had "a character all its own," with more crispness and rattles than the second stage. After 11 minutes and 42 seconds, the S-IVB single J-2 engine completed its first burn and switched itself off. The astronauts were in orbit, gently restrained by the couch straps, with a stunning view of the world through the spacecraft windows.⁴⁷

Over Australia the crew received word that they were "go" for the translunar injection (TLI) to boost the spacecraft out of Earth parking orbit into the trajectory to take it to the moon. This procedure required a second burn of the S-IVB. As the spacecraft swept out over the Pacific Ocean, the Saturn prepared to pump hydrogen and oxygen to the J-2 engine and meticulously dictated the orientation of the spacecraft by computers. The crew had no control over the vehicle at this point and were merely observers of the flickering lights on the panel indicating that the Saturn was counting itself down to ignition. When the J-2 finally started up, Neil Armstrong emitted a heartfelt "whew." Collins felt both relief and tension that they were on their way to the moon, one more hurdle behind them, as long as the S-IVB continued to burn. "If it shuts down prematurely," Collins speculated, "we will be in deep yogurt," ending up in a kind of odd-ball trajectory that would take some fancy computations on the part of Houston and the crew members to get back on track and set up for a reentry to Earth. Collins was amazed to see flashes and sparks of light, evidence of the thrusting engine mounted on the tail of the vehicle 33 meters below him. Abruptly a sudden lurch, like the shifting of gears, indicated that the Saturn had gone into a programmed shift in the ratio of fuel to oxidizer flowing to the engine. "Marvelous machine!" Collins thought to himself. "It's pushing us back into our seats with almost the same force we are accustomed to on earth (one G), although it feels like more than that. It's still not smooth, 'just a little tiny bit ratty,' says Buzz, but it's getting the job done and our computer is spewing out numbers which are very close to perfection."

STAGES TO SATURN

The shaking was more noticeable in the final moments of the ride, but ended with a good shutdown of the engine. "Hey, Houston, *Apollo 11*. That Saturn gave us a magnificent ride," Armstrong exclaimed.⁴⁸

On 20 July, as the spacecraft passed around the far side of the moon, Armstrong and Aldrin separated the lunar module from the command and service modules and began their descent for the lunar landing, leaving Collins in a station-keeping orbit above. During the final approach, the crew realized that the lunar module was headed toward a large, inhospitable crater filled with boulders. Taking over manual control of the descent rate and horizontal velocity, Armstrong steered toward a landing site several kilometers away from the original target area. At 4:18 p.m. EDT, the lunar module touched down. Armstrong reported to Earth: "Houston, Tranquility Base here—the Eagle has landed." With obvious relief, Mission Control in Houston called back: "Roger, Tranquility. We copy you on the ground. You got a bunch of guys about to turn blue. We are breathing again. Thanks a lot." Television cameras attached to the lunar module were oriented to catch Armstrong as he crawled out of the spacecraft. At 10:56 p.m. EDT, Armstrong stood on the lunar surface. "That's one small step for man—one giant leap for mankind."

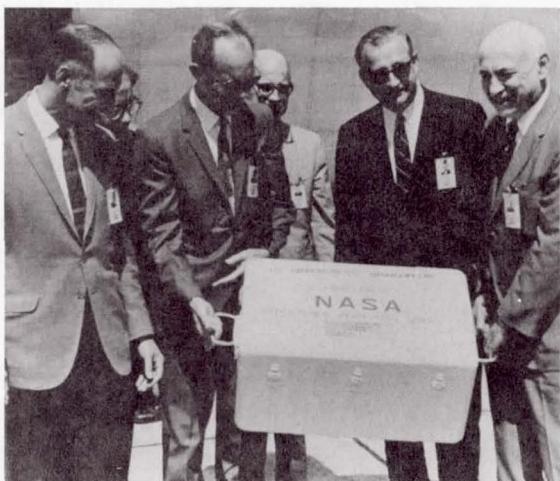
Armstrong was joined by Aldrin several minutes later, and the two men carried out a brief ceremony, unveiling a plaque fixed on one of the LM struts ("Here men from the planet earth first set foot on the moon July 1969, A.D. We came in peace for all mankind."), and set up a small U.S. flag. During their stay on the moon, Armstrong and Aldrin deployed a series of scientific experiments and picked up assorted surface material and chunks of rock, along with two core samples, all totalling about 24 kilograms. Their tasks accomplished, the pair of astronauts took off in the LM early in the afternoon of 21 July. Following the rendezvous in lunar orbit, Armstrong and Aldrin joined Collins in the CSM. The LM ascent stage was jettisoned, and a CSM engine burn on 22 July put them on a trajectory back to Earth. The command module made its programmed separation from the service module on the morning of 24 July 1969, and *Apollo 11* splashed down in the middle of the Pacific, only 24 kilometers from the recovery ship U.S.S. *Hornet*, at 12:51 p.m. EDT. The first moon mission was over.⁴⁹

LAUNCHES ON SCHEDULE: AS-507 THROUGH AS-512

Although other major launch vehicles, including the Saturn I, required a number of development flights, no major redesign efforts were required for the Saturn V. Even Apollo 6, the troublesome AS-502 vehicle, had required only moderate design changes to eliminate the Pogo difficulties and the problem with the J-2 engine igniter lines. This



Apollo 11 reaches the thin air on the edge of space (above, left); in the control room, NASA leaders (above, right to left) Charles W. Mathews, Wernher von Braun, George E. Mueller, and Samuel C. Phillips celebrate the orbiting of Apollo 11; left, Astronaut Edwin E. Aldrin, Jr., is photographed by fellow astronaut Neil A. Armstrong as he prepares to take his first step onto the lunar surface; below, left to right, George M. Low, Samuel C. Phillips, Thomas O. Paine, and Robert R. Gilruth admire the first box of lunar samples to be returned to Earth.



STAGES TO SATURN

observation is not to say that there were no variations among vehicles or changes from one vehicle to the next. Adjustments were made in timing, sequences, propellant flow rates, mission parameters, trajectories. There was continued modification and refinement in the course of the program. Each mission also produced a list of malfunctions, anomalies, and significant deviations that required certain configuration or operational changes. Engines and other equipment were constantly submitted to fine tuning to ensure and enhance their proper operation in flight. It is interesting to note, for example, that the thrust of individual engines varied even within a vehicle and from one mission to another, as technicians continued to adjust and change their operational characteristics.⁵⁰

The remaining six vehicles in the Apollo-Saturn program reflected this low-profile improvement and modification program. There were no major vehicle changes, and no catastrophic perturbations in the operational history of the Saturn V launch vehicles, although there were still dramatic moments and small problems that continued to crop up from time to time. The flight of *Apollo 12* was electrifying, to say the least. Before it got away on 14 November 1969, the vehicle had been delayed by a liquid-hydrogen fuel tank leak, threatening to scrub the mission. When that problem was finally whacked, stormy weather on the morning of the launch portended additional delays. With a long string of successful flights behind them, however, NASA officials decided to go ahead and commit *Apollo 12* in the midst of a heavy downpour. As it climbed away from the launch pad, AS-507 was lost to sight almost immediately as it vanished into the low-hanging cloud layer. Within seconds, spectators on the ground were startled to see parallel streaks of lightning flash out of the cloud back to the launch pad. Inside the spacecraft, Conrad exclaimed, "I don't know what happened here. We had everything in the world drop out." Astronauts Pete Conrad, Richard Gordon, and Alan Bean, inside the spacecraft, had seen a brilliant flash of light inside the spacecraft, and instantaneously, red and yellow warning lights all over the command module panels lit up like an electronic Christmas tree. Fuel cells stopped working, circuits went dead, and the electrically operated gyroscopic platform went tumbling out of control. The spacecraft and rocket had experienced a massive power failure. Fortunately, the emergency lasted only seconds, as backup power systems took over and the instrument unit of the Saturn V launch vehicle kept the rocket operating. As the huge Saturn continued to climb, technicians on the ground helped the astronauts weed out their problems, resetting circuits and making sure that operating systems had not been harmed by the sudden, unexplained electrical phenomenon. *Apollo 12* went on to complete a successful mission, and NASA scientists explained later that Apollo had created its own lightning. During the rocket's passage through the rain clouds, static electricity built up during

its ascent through the cloud cover had suddenly discharged and knocked out the spacecraft's electrical systems in the process.⁵¹

The *Apollo 12* mission survived the lightning charge for a number of reasons, but one significant factor was related to the ingrained conservatism at Huntsville in designing the rocket booster engines. During one early phase in planning the Apollo-Saturn vehicle, there had been considerable debate about designing spacecraft guidance and control systems to take charge of the entire launch vehicle, including the booster stages. Marshall had opposed the idea, arguing that the requirements of translunar guidance and control, lunar orbit control, lunar module rendezvous, and other jobs would be plenty for the spacecraft computer to handle. The peculiarities of the booster stages predicated quite dissimilar computer functions and schemes for guidance and control. Marshall finally won its case: the booster stages got their own guidance and control equipment, represented by the instrument unit. Besides, this approach provided redundancy, because the spacecraft got a separate system. An external umbilical connection between the command and service modules made the spacecraft guidance and control system vulnerable to the lighting charge. When the spacecraft gear was knocked out on *Apollo 12*, the booster guidance and control system, a separate piece of hardware, kept the vehicle operating and on course while the spacecraft electronics were reset and put back in operation. This vignette of Apollo-Saturn operational lore was a favorite of several MSFC managers.⁵²

Apollo 13 got off successfully on 11 April 1970. Because Thomas K. Mattingly II had failed to develop immunity after exposure to German measles, there was a last-minute substitution in the three-man crew, with John L. Swigert replacing him as command module pilot, joining Fred W. Haise, Jr., as lunar module pilot, and James A Lovell, Jr., as commander. The launch vehicle created some consternation among the mission officials monitoring AS-508 in flight, because the center engine of the S-II stage cut off 132 seconds too early, and the remaining four J-2 engines burned 34 seconds longer than predicted. This left the space vehicle with a lower velocity than planned. Therefore, the S-IVB had to burn nine seconds longer than predicted to achieve proper orbital insertion. This hiatus in the boost phase of the mission led to questions about adequate propellants remaining in the S-IVB for the translunar injection burn. Double-checked calculations indicated that there were adequate propellants, and the second S-IVB burn put *Apollo 13* into trajectory toward the lunar surface. The remainder of the flight was normal until about 56 hours after liftoff, when Swigert tensely called back to Mission Control, "Hey, we've got a problem here." With sudden concern, ground controllers responded, "This is Houston, say again please." This time Lovell replied, "Houston, we've had a problem."

An explosion had occurred in the No. 2 oxygen tank of the service

STAGES TO SATURN

module. As a result, all fuel-cell power was lost, as well as other CSM failures, including dangerously low oxygen supplies. Astronauts and mission controllers quickly agreed to abort the mission and concentrate on getting the three-man crew safely back home. *Apollo 13* went into a "lifeboat mode" with emergency measures to stabilize the spacecraft environment and stretch the consumable items for life support as far as possible. Using the descent engine of the lunar module after completing a lunar flyby, *Apollo 13* went into a return trajectory at a faster rate. Happily, the tense six-day mission ended successfully on 17 April, with splashdown in the Pacific Ocean. In the aftermath of the near disastrous flight of *Apollo 13*, NASA convened a special *Apollo 13* review board. Working in high gear, the board's painstaking research pinpointed the problem as a pair of defective thermostatic switches that permitted dangerously high heat levels in a heater tube assembly associated with the oxygen tank equipment. The board stated that combustion probably occurred as the result of a short circuit from faulty wiring, resulting in a combustion in the oxygen tank. Following release of the board's report, there was extensive redesign of the oxygen tank, wiring, and related materials with a high combustion probability. There was an impact on the launch of *Apollo 14*, which was slipped to 31 January 1971.⁵³

An interesting sidelight of the flight of *Apollo 14* involved the three-man crew, which included astronaut Alan B. Shepard, who had flown on the first U.S. suborbital launch in the Mercury program back in 1961. A decade later, Shepard was going to the moon. The countdown and launch of AS-509 proceeded according to the book, with the only delay caused by high overcast clouds and rain that postponed the ignition by 40 minutes and 3 seconds. Failure of a multiplexer in the instrument unit meant that some information on the condition of the vehicle during flight was lost, and there were some minor problems during the docking maneuver in orbit. Aside from that, *Apollo 14* was a perfect mission.⁵⁴

The last three vehicles, AS-510 through AS-512, performed without a hitch. The payload, however, was continuously climbing. These last three launches included the lunar rover vehicle, which added almost 225 kilograms to the payload of the Saturn V. The rover turned out to be extremely significant, permitting astronauts to extend greatly the range of surface explorations and increasing their stay time.⁵⁵ The uprated engines of the Saturn V, which permitted it to boost this additional weight into orbit, turned out to be a function of thoughtful long-range planning by NASA engineers. In the evolution of rocket vehicles, the actual payload requirements almost always turned out to be greater than originally planned. As a result of bitter experience, engine designers kept in mind the likelihood that their creations would have to be uprated from time to time. In addition to this consideration, engine designers normally incorporated a certain degree of margin in setting up the specifications for engine development. If the specifications called for an engine of 4.5

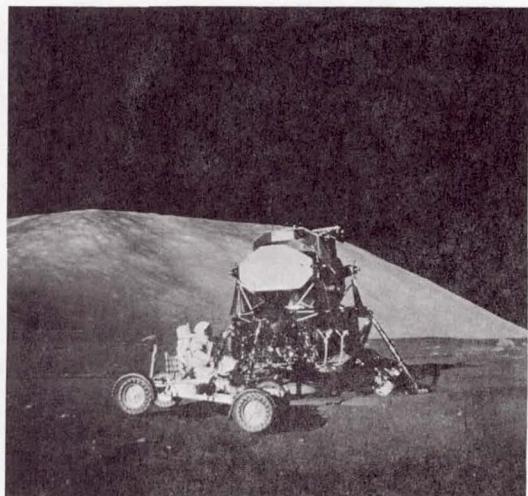
THE GIANT LEAP

million newtons (1 million pounds) thrust, it might be designed for 5.3 million newtons (1.2 million pounds) thrust to be sure that the original specification line was met. With operational experience, it was then possible to uprate the engine by relatively minor changes—improving the turbopump and the tubing (to improve flow rates), adjusting the injector for better mixing (to get a higher percentage of the fuel burned and increase the specific impulse)—these all were contributing factors to the success of uprating the engines of the Saturn V vehicle. In this way, the Saturn V was able to absorb not only the increasing weight of the command and service modules early in the program, but the added weight of scientific equipment and other paraphernalia such as the rover in the later stages of the Apollo-Saturn program.⁵⁶

SUMMARY

Saturn I and Saturn IB missions had been intended to clear the way for Saturn V launch vehicles. Normally, the worst difficulties would have shown up in the R&D flights of the former. Instead, one of the most baffling periods came early in the Saturn V flight series.

Saturn V development began auspiciously, with the calculated gamble on AS-501's "all-up" launch. The mission garnered precious time and raised confidence in the reliability of Saturn stages. The time and reliability factors seemed to slip away, however, with the perplexing flight of AS-502 and slipping schedules for the lunar module to be flown on AS-503. Recovering quickly, NASA and contractor personnel kept the momentum of Apollo-Saturn through diligent sleuthing to resolve the problems uncovered in AS-502 and responded flexibly to revise the



By the time the Apollo program ended with Apollo 17, the uprating of Saturn V engines was allowing heavier payloads on the lunar surface, including the lunar roving vehicle, which so dramatically increased the mobility of exploring astronauts.

STAGES TO SATURN

probable mission of AS-503. In light of its uncertain background, the circumlunar flight of *Apollo 8* was a triumph.

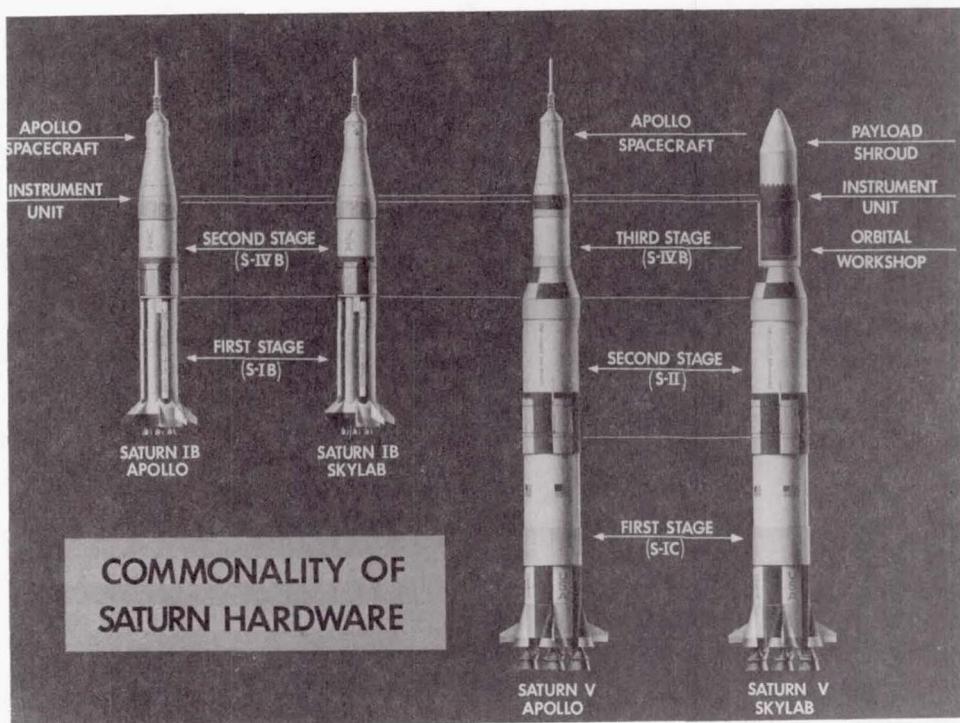
There were two more Saturn V launches, wringing out the last details of mission hardware, before AS-506 took a crew to the lunar surface and back. *Apollo 11* was a textbook flight, carried out in an unprecedented public exposure of worldwide dimensions. From beginning to end, it was a spectacularly successful mission, a historic odyssey in the annals of human exploration. The remaining six missions in the Apollo program were completed with no major difficulties stemming from the launch vehicles. In retrospect, the conservative design inherent in the Saturn launch vehicles paid off. Saturn V not only carried a spacecraft and lunar module whose weight had spiraled upward from original guidelines, but accommodated additional equipment such as the lunar rover. The added payload capability of the Saturn V also permitted delivery of more scientific gear to the moon, enhancing the scientific results of the Apollo-Saturn missions.⁵⁷

VIII

Epilogue

Both the Soviets and the Americans used their man-rated space rockets for a variety of missions. NASA used basic Saturn hardware for launching the Skylab space station; Skylab itself evolved from the Saturn V third stage. The last Saturn rocket to be launched culminated in the linkup of a manned American spacecraft with its manned Soviet counterpart—the Apollo-Soyuz Test Project.

Thus, one of the legacies of what started as a race in space ended in a new arena of international cooperation. The Saturn program left other legacies. The city of Huntsville, Alabama, entered a new era of social and economic vigor, since Marshall Space Flight Center's activities attracted nonspace commercial enterprises to a booming locale and injected vitality into health care, education, municipal services, and the arts. Finally, execution of the Saturn program stimulated significant research and improved technique across a wide range of fabrication and manufacturing processes.



13

Legacies

The Apollo-Saturn program began in an atmosphere of international competition, the object of which was to beat the Russians to a manned landing on the moon. In terms of heavy payloads and successful manned flights, Soviet boosters and aeronautical sophistication seemed to set the pace for the exploration of space for several years after Sputnik. The Gemini program of the mid-1960s considerably enhanced American skills in manned space flight, and development of the Saturn I, Saturn IB, and Saturn V gave the United States a booster capability that surpassed the Soviet boosters. With the three-man Apollo spacecraft, the Apollo-Saturn combination carried not one, but seven manned missions to the lunar surface. In big boosters, where the United States had always lagged, Saturn finally retired the cup.

The Soviet space program conducted an impressive series of unmanned research missions, including remote reconnaissance and sampling of the lunar surface by robots, and the return of small samples to Earth. Yet the Russians had not landed a cosmonaut on the moon by the mid-1970s despite some spectacular manned missions, involving orbital rendezvous, docking, and crew transfer, using Soyuz spacecraft. Although the Russians successfully orbited their Salyut space station in combination with manned Soyuz launches in 1971, *Soyuz 10* did not complete the transfer of the three cosmonauts and the crew of *Soyuz 11* died during reentry.

In the meantime, the American space program was also moving ahead with a variety of unmanned satellites and probes, and the momentum of Saturn resulted in a genuine space station, the Skylab. The last launch of a Saturn vehicle was a singular event, achieving orbital

STAGES TO SATURN

linkup of manned spacecraft—one from the U.S. and the other from the U.S.S.R.

SATURN, SKYLAB, AND APOLLO-SOYUZ

Skylab was the final version of several plans to modify the Saturn S-IVB stage so that it could be occupied by astronauts in space. The Skylab assembly consisted of several modules, including the orbital workshop (a modified S-IVB stage), airlock module, multiple docking adapter, and Apollo telescope mount. This modular payload was launched to low Earth orbit aboard a two-stage Saturn V, with the Skylab in the upper position normally occupied by the S-IVB third stage.

The idea of using a Saturn stage as a space station apparently developed while planning Saturn I and Saturn IB mission profiles. In the normal sequence of events, S-IV and S-IVB upper stages of these vehicles became space-age "orphans." Their propellants expended, the empty stages remained uselessly in orbit. With such large tanks circling the Earth, it was not long before some thoughtful engineers wondered why it would not be possible to use an empty stage as a habitat for astronauts. In November 1962, Douglas Aircraft, the S-IVB contractor, published a short study suggesting the use of the S-IVB as a laboratory in space. A group of engineers at MSFC evidently had a parallel concept in mind, although they had not yet committed anything to paper.

During the next few years, the increasing tempo of the Apollo-Saturn program absorbed the thoughts and energies of planners at both Douglas and Marshall Space Flight Center, and nothing was accomplished in terms of turning a spent stage into a space laboratory. Early in 1965, however, program analysts at MSFC who were thinking ahead began to use the terms "spent stage" and "wet workshop" in talking about refurbishing the S-IVB in orbit and using it as a laboratory. The idea lacked programmatic approval or support until early August, when George Mueller announced the organization within Headquarters of an Apollo Applications Program Office to extend use of the hardware developed for Apollo-Saturn. Late in August, as part of Marshall's contributions to the Apollo Applications Program (AAP), a full-fledged design study was initiated to examine the concept of the spent stage laboratory and to come to some conclusions about its potential. On 1 December 1965, George Mueller gave the go-ahead for what was now called the orbital workshop, with MSFC as the lead center in the project.

The overall AAP, including the orbital workshop concept, originally contemplated a large number of both Saturn IB and Saturn V vehicles. In 1966, one early planning schedule called for 26 IB launches (primarily to carry three-man crews), and 19 Saturn V launches. Three S-IVB spent stages, three Saturn V workshops, and four Apollo telescope mounts

were to be orbited. Included in this ambitious schedule were five more lunar missions and two synchronous-orbit missions. The S-IVB spent stage would be converted to a lab by use of the spent-stage experiment support modules. Mounted on the forward end of the S-IVB, this module was a docking facility and airlock for the Apollo command and service modules. Because the S-IVB lacked crew quarters, the crew would live and conduct biomedical experiments in the command module, while the empty S-IVB would provide a suitable environment for familiarization with zero-g conditions in a comparatively large enclosed environment in space.¹

By December 1966, plans called for a "wet" workshop, created by purging and then pressurizing the hydrogen tank in orbit to create a working environment inside. A significant addition to the scheme was an Apollo telescope mount, to be carried into orbit by another Saturn IB and connected to the orbiting workshop. Between 1967 and 1969, the plans for the workshop concept shifted with budgetary constraints and available hardware. Finally, in July 1969, Administrator Paine announced that the "wet" workshop was being dropped in favor of a "dry" workshop. Under this new approach, the workshop and the Apollo telescope mount were to be launched together by using the first two stages of the Saturn V (instead of an uprated Saturn I). All equipment, expendables, and experiments would be installed ahead of time in the workshop, ready for use when the astronaut crews made their rendezvous and docked. In August 1969, McDonnell Douglas became the contractor for two Saturn V workshops. The first workshop was scheduled for launch into a low Earth orbit sometime in 1972, with the second version serving as a backup.²

Early in 1970, NASA Headquarters announced that the AAP would henceforth be called the Skylab Program. In addition MSFC announced that the Saturn IB, carrying the three Skylab astronauts, would be launched from the modified Launch Complex 39B at Cape Kennedy. The Skylab Program at this time called for launch of the Skylab from LC 39A, followed the next day by a Saturn IB launch carrying the astronauts. The first crew was programmed to spend 28 days in orbit, and within the next six months, two more manned missions would put three-man crews into the Skylab for approximately 56 days apiece. Following these missions, Skylab would then be put into a storage mode, remaining in orbit.³

Developmental and technical problems created a delay in the anticipated launch date, which was finally rescheduled for the spring of 1973. Meanwhile the Saturn IB first stage for the first manned Skylab launch vehicle was taken out of an environmentally controlled enclosure at the Michoud Assembly Facility, where the stage had been in hibernation for three years. This particular booster was one of nine such Saturn IB stages stored at Michoud in December 1968. Altogether, four Saturn IB stages were designated for the Skylab project: AS-206, AS-207, AS-208, and

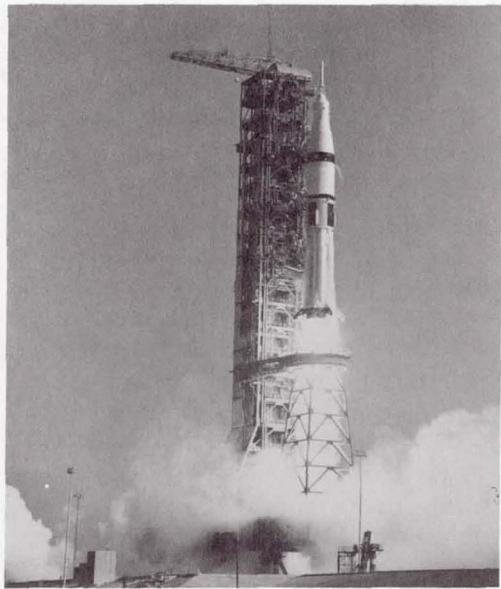
STAGES TO SATURN

AS-209. Refurbishment of each vehicle was estimated at approximately 10 months. The AS-209 vehicle served as the backup stage, in case a possible rescue mission needed to be dispatched to the Skylab in orbit, using a modified CSM to return five astronauts.⁴

On 14 May 1973, the Skylab went into orbit aboard the AS-513 booster. Skylab was a fairly roomy space station, about as large as a medium-sized two-bedroom house, and provided a true "shirt-sleeve" environment for the astronaut crew, permitting them to live and work inside the Skylab without cumbersome space suits. NASA technicians soon realized, however, that something had gone very wrong. During the launch, a protective micrometeoroid and heat shield was torn loose, and one of the two solar power arrays, to provide electrical power to the Skylab, was also ripped away. The remaining solar wing was only partly deployed, and lack of power allowed the temperatures inside the Skylab to soar. A crash program by NASA and contractor technicians came up with a possible solution in the form of a large parasol device to deflect the sun's rays and reduce interior heat. With special equipment to set up the parasol and cut away the debris to free the solar wing, the first Skylab crew took off much later than originally planned, on 25 May 1973.

After docking, deployment of the sunshade cut the high temperatures inside Skylab, allowing the crew to move in. Still, because of the jammed solar panel, problems of temperature control and inadequate power persisted. Working outside the Skylab and using the tools brought along for this specific task, astronauts Charles Conrad, Jr., and Joseph Kerwin finally freed the power panel. The makeshift shade, plus partially restored power, reduced interior temperatures to comfortable levels, and the mission proceeded. The three-man crew spent a month in space, after adjusting to early discomfort from extended weightlessness. On their return, physicians endorsed ambitious plans for the two succeeding crews to stay up from two to three months. The second Skylab crew, launched on 18 July 1973, spent 59 days in orbit; the third crew, launched 16 November 1973, spent a record-breaking 84 consecutive days in space before splashdown on 8 February 1974. One of the major contributions of the Skylab program was convincing proof that crews could indeed spend extended period in weightlessness, perform effectively, and suffer no harmful effects on return.

In addition to these invaluable biomedical records and results, the Skylab crews conducted a wide variety of sophisticated experiments on the characteristics of the Earth's environment and resources, collected data on the sun and the solar system, and experimented with possible types of esoteric industrial processes that could be enhanced by performing them in the environment of space, avoiding the perturbing factors of the Earth's rotation and effect of gravity. Some of the more significant astronautical work during the Skylab missions involved extended observations of an unusual period of solar flare activity in 1973. Late in the



Left, a Saturn IB lifts from Launch Complex 39 to send Skylab 4 on the final orbital mission with the Skylab orbital workshop (right), which had been previously orbited on the last Saturn V flight. The three Saturn IB launches in Skylab employed the foreshortening tower (seen here) as a base so that they could use the Saturn V umbilical tower.

year, the astronauts took advantage of a target of opportunity and studied the newly discovered comet Kohoutek from their unparalleled point of view in space. In total, the Skylab missions accumulated extensive new knowledge of the oceans, weather formation and climate, pollution, and natural resources.⁵

The last Saturn vehicle to be launched was AS-210, on 15 July 1975. Although the Satellites were originally developed in response to what was seen as intense Soviet competition for domination in space, the last flight of a Saturn launch vehicle featured a cooperative mission with the Soviets in space. This was the Apollo-Soyuz Test Project (ASTP). The mission involved the joining, in Earth orbit, of spacecraft of the United States and the Soviet Union. Following many months of preliminary talks and agreements, in May 1972 the Russians and Americans agreed to work out a common docking system for future generations of spacecraft, leading to the ASTP mission. The mission marked the first time that manned spacecraft of different nations met in space for cooperative engineering and scientific activities.

The ASTP launch vehicle's first stage had been built by the Chrysler Corporation at Michoud Assembly Facility in January 1967. Following static-firing tests in the spring of 1967, the stage was put in storage at Michoud, where it remained until October 1972. After the first stage was

STAGES TO SATURN

modified, refurbished, and checked out, it was shipped to KSC in April 1974. After more months of storage, the first and second stages were stacked, and the vehicle was placed on the mobile launcher in January 1975. The S-IVB second stage was of the same vintage, completed in 1967 by McDonnell Douglas at Huntington Beach, California, and was stored there until the fall of 1972, when it was shipped to the Kennedy Space Center. The instrument unit, built by IBM, shared a similar manufacturing and storage history. It was shipped to KSC by barge in May 1974. After stacking, the entire vehicle was rolled out to the launch pad late in March 1975; continuous preflight checkouts and monitoring of the launch vehicle were made until launch that summer.⁶

The Russians were also preparing their launch vehicle and spacecraft. Considerable exchange of technical information was required between Soviet and American mission personnel. Most of these contacts concerned spacecraft, docking, telemetry, and crewmen. Even with the insights gained into Russian aeronautical technology acquired as a result of the ASTP collaboration, public knowledge of Soviet launch vehicles is still sketchy in many details. As far as the engines are concerned, the Russians apparently based their propulsion systems on technology garnered from the V-2s wrested from Germany after World War II. Like the Americans, Russians technicians got their early experience in launching captured German weapons and then produced a series of modified V-2s as they began to develop their own ballistic missile technology. Early in the 1950s, the Russians evidently began work on a very large propulsion system planned for their first ICBM and considered using this propulsion system in space programs as well.

Although extrapolated from V-2 engine technology, this new Soviet engine incorporated a somewhat novel arrangement, featuring multiple combustion chambers. The physical appearance of the engine, with its quartet of combustion chambers, normally creates some confusion in the mind of an observer who associates American-style engines with a single turbopump, combustion chamber, and exhaust nozzle. In the Russian version, a single turbopump fed the oxidizer and fuel to a combination of combustion chambers. Thus, while appearing to be a cluster of engines, it is actually a cluster of four combustion chambers and exhaust nozzles. The Russians designated this propulsion system the RD-107. The RD-107 burned kerosene-type fuel and liquid oxygen, and the cluster of four combustion chambers and exit nozzles produced a total thrust of 1 000 400 newtons (224 910 pounds). The turbopump was fueled by hydrogen peroxide. This engine system did not have a gimbaling capacity, but included two small steering rockets. The Soviets produced a variant of this engine system known as the RD-108, which differed from its cousin only in the fact that it had four small steering rockets instead of two.

The combination of these engine systems as a single booster powered the series of large Soviet launch vehicles, including the Sputnik, and

with further variations in the upper stages, the Vostok, the Soyuz, and the Salyut space station. The basic launch vehicle was known in the United States as the type "A" booster, and it was also used by the Russians for some unmanned payloads.

The booster design situated the RD-108 as the central core engine, also acting as a sustainer engine. Then four RD-107 engines, with long streamlined fairings, were clustered about this central core. Integration of the parts of the launch vehicle and attaching the payload took place in the horizontal position. Still horizontal, the entire vehicle was rolled out on a conveyor that resembled a railroad flatcar and positioned in the upright launch position at the launch pad. The Sputnik booster was a single-stage vehicle, although the Vostok, Soyuz, and Salyut vehicles incorporated upper stages that apparently used similar liquid oxygen and kerosene propellants. In the launch sequence, all the first-stage engines were ignited on the pad. The ignition meant a striking liftoff, with 20 main engine nozzles spouting flame, accompanied by the exhaust plumes of the 12 steering rockets. All 20 main engines continued to function during the boost phase. As propellants were depleted in the four outboard RD-107 engines, these fell away, leaving the RD-108 (the central sustainer unit), which continued to fire. Depending upon the nature of the mission programmed for the upper stages, the central core then separated from the upper-stage combination late in the boost phase, and a combination of upper stages put the payload into orbit or a space trajectory. The Russian launch vehicle, with its four elongated RD-107 streamlined units, looked rather graceful, more like a Buck-Rogers-type rocket than some of the American boosters.⁷

In retrospect, these Russian launch vehicles of the A series appear to be somewhat less sophisticated than their American counterparts, but no less effective in getting heavy payloads into orbit. As ex-Soviet engineer and editor Leonid Vladimirov pointed out, the RD-107 system took up more space than a comparable single-chamber engine of the same power. This meant that the diameter of the first stage of the launch vehicle was also larger, resulting in a considerably greater launch weight. For this reason, the jettison of the four outboard engine systems, leaving the sustainer to carry the vehicle into orbit, was an important design feature of the Russian launch vehicles. "It was, of course, a very complicated, costly and clumsy solution of the problem," Vladimirov admitted. "But it was a solution nonetheless; all launches of Soviet manned spacecraft and all the space-shots to Venus and Mars have been carried out with the aid of this monstrous twenty-engined cluster."

There were other interesting variations in U.S. and Soviet booster technology. The tank skins and structural elements of American vehicles were kept at minimum thicknesses, shaving the weight of the structure as much as possible to enhance the payload capability. The first Western insight into the style of Soviet vehicle structure occurred in 1967, when

STAGES TO SATURN

the Vostok spacecraft and booster system were put on display in Paris. The Russians series of A-type vehicles appear to have been exceedingly heavy. The Vostok launch vehicle arrived via Rouen, France, by sea, prior to shipment to Paris. To move the tank sections of the launch vehicle, workers hooked up cables to the opposite ends of the tank sections and picked them up empty, surprising many Western onlookers who expected them to buckle in the middle. Their amazement was compounded when the Soviet technicians proceeded to walk the length of these tank sections, still suspended in mid-air, without damaging them in the least. The Russian vehicles were, if anything, extremely rugged. The launching weight of the Vostok and spacecraft is still a matter of conjecture because the Soviets have not released specific numbers. Vladimirov estimated around 400 metric tons on the ground, with the greater part of the weight accounted for by the heavy engines. He drew an interesting comparison between the Soviet type A vehicle and the American launch vehicle known as the Titan:

[The Russian vehicle] had a total thrust from the engines of its first stage of 500 tons which put into orbit a load weighing only 40-45% more than the weight of *Gemini*. You simply have to compare the *Titan's* 195-ton thrust for a three and a half ton useful load with the Soviets rockets 500-ton thrust lifting a five ton load.⁸

Although the Russians never really developed a launch vehicle with the capability of the Saturn V, they apparently attempted to do so. Rumors of this new vehicle, known as type G, gained currency following a space conference in Spain in 1966. Rather than develop new, exotic high-energy propellants and propulsion systems, Soviet designers reportedly used engines from advanced ICBMs and clustered a large number of chambers to achieve high thrust. The type G booster was rolled out during the summer of 1969, but during a static test, a leak evidently began in one of the upper stages, developed into a fire, and destroyed the entire vehicle. The disastrous fire also wiped out the launch facility, including underground equipment complexes as well as service towers and other support equipment at the launch site. Reports indicate that a type G vehicle was launched in midsummer of 1971, but the rocket broke up and disintegrated before reaching orbit. In November 1972, the Russians made one more attempt to launch the big type G rocket. Bad luck continued to plague the effort, and the 1972 mission also ended in disaster, apparently because of a failure in the first stage. As 1975 came to a close, development of the type G seemed to be in a state of limbo.⁹

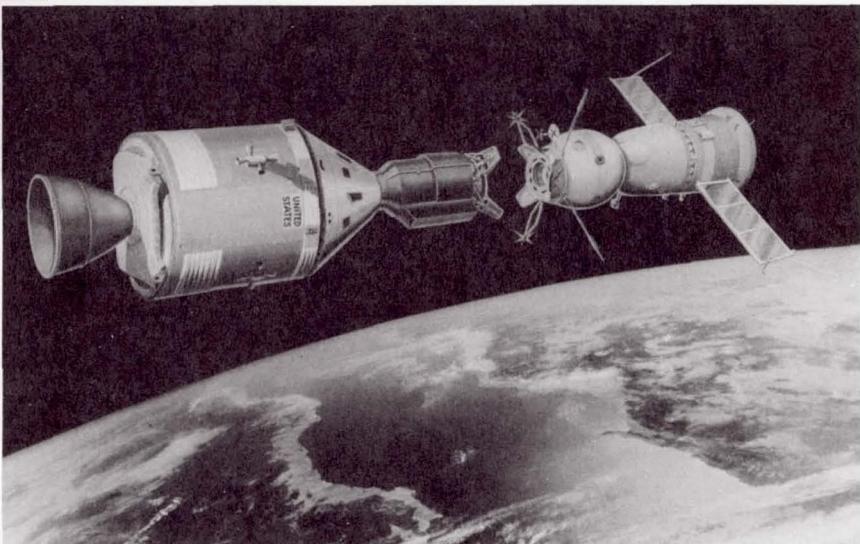
Thus, the Soyuz spacecraft for ASTP relied on the time-tested type A booster. According to plan, the Russians launched first, early in the morning of 15 July, when cosmonauts Aleksey Leonov and Valery Kubasov lifted off from the Soviet Cosmodrome at Baykonur in Central Asia. Seven and a half hours later, the Saturn IB lifted off from Cape

LEGACIES

Kennedy, Florida, carrying American astronauts Thomas P. Stafford, Vance Brand, and Donald K. Slayton.

The ASTP mission was a perfect finale for the Saturn program. The countdown for the launch vehicle and performance during the boost phase proceeded without a hitch. MSFC press releases noted that the Saturn IB carried the oldest engine yet flown, a nine-year-old veteran.¹⁰ After ASTP, the inventory of Satellites in storage consisted of two Saturn IB vehicles, SA-209 (backup for both the Skylab and the ASTP missions) and SA-211, and two unassigned Saturn V vehicles, SA-514 and SA-515.

The Apollo-Soyuz Test Mission began with the launch of the Soyuz spacecraft (left) from the Soviet Union, followed by the S-IB launch of the Apollo spacecraft from KSC. Below is an artist's concept of Apollo and Soyuz as the Apollo spacecraft edges in for the first international docking in space.



STAGES TO SATURN

Behind these retired symbols of space exploration, the proficiency of MSFC persisted. With its competence in propulsion systems, Marshall was given responsibility for development and management of engines for the shuttle program, conducted R&D programs in space tracking and communications, and studied various space payloads for the future. In short, MSFC carried on a continuing influence in Huntsville and northern Alabama and in the nation's space program.

ASTRONAUTICS IN HUNTSVILLE

The elaboration of the nation's space program in the 1960s and early 1970s had an obvious impact in the south and southeast, anchored by major NASA centers. NASA's geographic influence in the region stretched along a great arc, from the Manned Spacecraft Center in Texas, to Marshall Space Flight Center in Alabama, to Kennedy Space Center in Florida. In between were MSFC's "satellites" near New Orleans: the Michoud Assembly Facility, the Slidell computer complex, and the Mississippi Test Facility. This concentration of space-related expertise and activities has been described as "a fertile crescent" of astronautical skills. Development of these centers of major NASA activities created extensive local and regional changes, and the story of the impact of NASA in Huntsville is paralleled in many respects by the events that occurred south of Houston and near the Kennedy Space Center.¹¹

Before the von Braun team came to Huntsville, Alabama, the town was known as "Water Cress Capital of the World." Its population was 16 000. Even so, this period of Huntsville's "salad days" continued strong ties with the cotton textile industry, and Huntsville once boasted 13 cotton mills in the area. Throughout the 1940s, the other major source of employment in the area had been the Redstone Arsenal. Established in 1941, the 1620-square-kilometer arsenal was used by the U.S. Army in the production and testing of chemical warfare weapons. After the war, it was shut down, declared surplus property, and put up for sale in 1949. Huntsville city fathers and local politicians, including Senator John Sparkman and Representative Bob Jones, were soon sounding out their contacts in the Department of Defense to see what could be done to keep the Arsenal alive. Jones and Sparkman were hot on the trail of a new location for wind tunnel test facilities for the Air Force, but lost out to the state of Tennessee. The wind tunnel was located at the recently closed Camp Forest at Tullahoma, and was eventually named the Arnold Engineering Development Center. Nevertheless, Sparkman and Jones had made an impression. Secretary of the Air Force Stuart Symington told Sparkman that Alabama would get something better in the long run. A few weeks later, the Alabama congressmen found out exactly what they

were acquiring—the Army's Rocket Research and Development Suboffice, to be relocated from Fort Bliss, Texas.¹²

Huntsville had been one of the several sites under consideration. The site selection committee included von Braun, and he was enthusiastic about Huntsville from the beginning. "For me, it was love at first sight," he said. Among other things, the advantages of Huntsville included the existing Arsenal facilities, abundant low-cost electric power from the TVA, the Tennessee River (both for water supply and transportation), and the open space. "In selecting this site, of course," von Braun recalled, "in our field we had to consider that these rockets would be making a lot of noise."¹³ After the arrival of the Army's missile agency in April 1950, Huntsville started its meteoric growth, from 16 000 in 1950 to 48 000 enumerated in a special census held in 1956. The 1960 census put the population of the city at 72 000; another special census in 1964 gave the population as 123 000; in 1970 it was 136 102. Construction boomed during the first half of the 1960s: the city of Huntsville was 195th in population in the United States, but ranked 25th in building construction.

In 1950, the city limits extended about one and a half kilometers from each side of the courthouse, encompassing 11.1 square kilometers, with roughly 125 kilometers of sewer lines but no sewage treatment plant at all. Huntsville's effluent was piped to a creek outside the city limits, where it was carried directly into the Tennessee River. Tax considerations and other agreements made earlier with the textile mills provided a stumbling block to city plans for enlarging the city limits, along with improving sewage facilities—which the Army was now insisting on. After numerous sessions lasting into the early hours of the morning, representatives from the city, the Army, and the mills came to an agreement, and in 1956 the city of Huntsville suddenly enlarged itself to over 181 square kilometers. Eventually, over 1300 kilometers of sanitary lines and a first-rate sanitation system served the area.¹⁴

The influx of Army personnel, NASA civil servants, and contractors, with their families, raised enrollments in the city schools from 3000 in 1950 to over 33 000 by 1974. The numbers barely suggest the problems involved in establishing classrooms, finding teachers, and creating appropriate curricula. Fortunately, among the families of the scientists, engineers, and technicians pouring into the city were spouses with teaching backgrounds to help staff the expanding school system. The schools developed a definite scientific-technological bent, probably encouraged by the frequent appearance of many of Marshall's top personnel as guests and speakers in school classrooms and assemblies. Huntsville's new population also gave the public schools a strong orientation to higher education, with 80–95 percent of Huntsville's high school students going on to college, in comparison to a state average of only 20

STAGES TO SATURN

percent. Rapid population growth also brought new challenges to Huntsville's medical facilities. The Huntsville Hospital had been built in the 1920s. By the early 1950s, patients were being placed in the hallways of the hospital, and an emergency expansion finally brought the hospital's capacity to 150 beds. Severe pressures for medical services persisted, and by 1970, Huntsville had four hospitals in operation with a total of almost 1000 beds.¹⁵

There was a parallel impact on higher education in the city. Since 1949, the Chamber of Commerce had been advocating a branch of the University of Alabama in Huntsville. A center was authorized, and 139 part-time students began classes in January 1950. The arrival of von Braun and the elaboration of Army research immediately stimulated a graduate program. In 1960, construction of a permanent campus began at the northern edge of the city, and von Braun appeared before the Alabama legislature in support of an appeal for a \$3-million bond issue to establish a research institute geared to graduate research at the new campus. The bond request was passed easily by the legislature and approved quickly by the voters, a success marking a sustained period of growth by the University of Alabama in Huntsville, with a student body of over 4000 and a replacement value of about \$30 million by 1974.¹⁶

The citizens of Huntsville always maintained a strong interest in cultural activities, with literary and music societies dating back several generations. The arrival of the culturally minded German rocketeers enhanced this tradition and left an imprint on the history of the arts in Huntsville. According to local legend, the Germans arriving in Huntsville equipped themselves with library cards even before the water in their homes had been turned on. The newcomers from Fort Bliss not only appeared in public school classrooms, giving informal lectures and talks, but were regular attendees at local PTA meetings. Acculturation was remarkably rapid. Three years after arriving in Huntsville, the DAR medal for the best American history student in the city went to a young German girl.

Wanting to avoid a German enclave in the middle of the city, von Braun encouraged his associates to settle all over Huntsville. The rocket engineers and the Huntsville natives soon established strong bonds of common interests and activities. A local chamber music group learned of the musical inclinations of many of the newcomers. The day he arrived, Werner Kuers, an accomplished violinist, was startled to receive a call to join one of the local music groups in need of a new violin. "I was very astonished," Kuers recalled. "Mr. Dreger soon started to arrange playing sessions for us in homes and churches. We were introduced into quite a number of very friendly families interested in cultural activities and education. I experienced a welcome in this city that I had never experienced before anywhere."

Thus, veterans of Peenemuende and of Fort Bliss were quickly absorbed into the life of Huntsville and into American culture. In April 1955, only five years after they had arrived in Alabama, the first group of 109 Germans became American citizens. Their naturalization took place at a public ceremony in the Huntsville High School auditorium, part of the officially proclaimed events of a "New Citizens' Day" declared by the city. Many of the newly naturalized American citizens had already taken an active role in civic affairs. A sergeant in the Luftwaffe when he was assigned to Peenemuende, Walter Wiesman joined the Junior Chamber of Commerce in Huntsville soon after the von Braun team's arrival in 1950. Two years later—before Wiesman became a naturalized citizen—the JCs elected him their president.¹⁷

In Marshall Space Flight Center's heyday, wags sometimes referred to Huntsville as "Peenemuende South." For years, the city proudly called itself Rocket City, U.S.A. Nevertheless, the city fathers, as well as von Braun himself, realized that federal budgets, like NASA's, had valleys as well as crests. It was widely agreed that Huntsville should expend considerable time and energy attracting other industries into the area. In later years, von Braun took a considerable measure of satisfaction in remembering his role as an advocate of diversification. "I can say in retrospect that I have never regretted using my powers of persuasion . . . in talks with the city fathers and our community advisory committee, when I always reminded people: 'Don't get too used to this NASA money that's flowing into this area.' " He warned against becoming a single-business town and advocated the attraction of other industries during a period of good stability, with attention to nonaerospace companies in particular.

The development of the industrial character of Huntsville frequently reflected the high-level technology represented by NASA and the U.S. Army Missile Command, on the site of the old Redstone Arsenal. The continuing development of the Cummings Research Park characterized this high-level technology. Located near the University of Alabama campus, the Research Park comprised over 30 companies that offered unique management services and research facilities and employed over 6000 people with an annual payroll of over \$93 million by 1974. In the 1960s, the emphasis was on space, but the farsightedness of von Braun and other Huntsville industrial executives maintained a healthy diversity in the city's manufacturing companies in the 1970s. At the Research Park and elsewhere, including an industrial center located near the new Jetport, Huntsville's products included automobile radios, digital clocks, electronic parts, computers, TV cameras, ax handles, flags, aircraft specialty glass, tools and dies, telephones, rubber tires, and a host of other goods and services.¹⁸

One of the most visible results of the von Braun team's sojourn in Huntsville was the new Von Braun Civic Center located downtown near a

STAGES TO SATURN

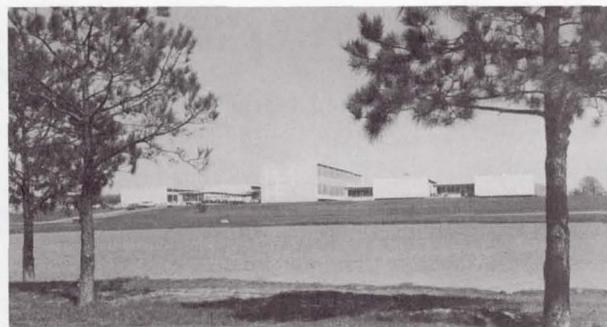
renewal area known as Big Spring Park. A \$14-million complex that opened in 1975, the center included a large arena, as well as a spacious exhibit hall. A concert hall and playhouse provided exceptionally fine facilities for both performers and audience. Finally, the performing arts in Huntsville were no longer dependent upon the good will of various churches and high school auditoriums. The homeless graphic arts of the city at last found, in the Von Braun Center, a handsome new creative arts museum, with arrangements for both permanent and visiting art exhibits. The city also acquired a major tourist attraction, the Alabama Space and Rocket Center. The Center not only coordinated tours at MSFC, but also mounted some innovative displays. Skillfully planned and automated dioramas and indoor exhibits explained the theory of the solar system, fundamentals of rocket propulsion, future space exploration, and numerous other aspects of astronautics. The indoor displays also featured an eye-catching array of aerospace hardware, including full-sized mockups of spacecraft and genuine artifacts such as Saturn engines. The most impressive section was outdoors, where a rocket display area included several Army missiles, a V-2, and several early NASA launch vehicles. Towering above them all, a Saturn I stood erect, and a complete Saturn V rocket, stretched out on its side, loomed as a backdrop.¹⁹

THE SIGNIFICANCE OF SATURN

Spinoff

The impact of the Saturn program in Huntsville was to be expected, but there were also much broader influences. Many Americans believed that the national space program would be the source of significant products for use in everyday life. Although many products found their way into ordinary life as a result of space research, the expectations for immediate impact were probably too optimistic. In his thoughtful and provocative book, *Second Order Consequences*, Raymond Bauer noted that the design and development of space hardware, systems, and subsystems were specialized from the beginning. It has not always been easy, therefore, to transfer technology into the market place.²⁰

This is certainly not to say that space technology has had no impact on American lives. In a larger sense, the operation of communications satellites, weather satellites, and environmental and resources satellites are only some examples. Biomedical research, including techniques for monitoring and analyzing an astronaut's life signs during a mission, has had a significant effect on medicine and hospital care. It has been frequently noted that the space program in general has had a tremendous influence on the electronics and computer industries in stimulating



Part of the legacy of the space program and Marshall Space Flight Center to Huntsville, Alabama: top left, the Research Institute of the University of Alabama in Huntsville; top right, Cummings Research Park; lower left, the Von Braun Civic Center; lower right, the Alabama Space and Rocket Center.

considerable research and providing job opportunities for thousands of workers and technicians.²¹

Nevertheless, the technology represented by the electronics and computer industries has benefited from the space program essentially in terms of second order consequences. Much of that technology and many of the techniques were developed for highly sophisticated and complex space programs, and only with some changing and adaptation were the technology and techniques found to be suitable for other civilian applications. This factor is an example of what Bauer and others have called the "intangible spinoff." Further, advances in this respect are important to

STAGES TO SATURN

technology for a couple of reasons. Taken individually, these incremental improvements contribute to overall efficiency and often to higher quality in day-to-day industrial operations in the production of goods and services. As Bauer emphasized, "Although the gain from application of a new welding technique may be small, the aggregate benefits of many such advances, applied in many industries and firms, can be quite large." In addition, Bauer emphasized it was possible for new methods, new advances, and new ideas to come together in some combination that would also result in a striking or significant new advance. "The convergence of a number of such improvements, along with technical advances arising in other fields, may make possible new fundamental inventions of substantial individual significance."²²

In the development of the Saturn vehicle, many spinoffs consisted of myriad improvements in the prosaic areas of shop work, although such improvements were usually the result of new fabrication technologies and use of advanced materials. William R. Lucas, a senior engineer at MSFC and later Director of the Marshall Space Flight Center, emphasized that the almost immediate usage of new aluminum alloys at MSFC undoubtedly encouraged further research and development in the field, including the development of additional alloys, thermal treatment, and fabrication processes. By the same token, new research and development work in the welding of aluminum alloys also took place.²³ Consistent with Bauer's comments about the significance of the accretion of technological expertise as well as the potential impact of convergence, one welding engineer at Marshall Space Flight Center posed this rhetorical question: "What has the space program contributed to welding technology?" The engineer admitted that the question was at once blunt as well as disconcerting—disconcerting, "because many of the contributions are quite subtle, beyond the reach of symbolism, and often never recognized."²⁴

Marshall's successful approach to welding problems was not so much a function of breathtaking or striking breakthroughs as it was a process of accretion and convergence: the application of improved techniques, thoughtful readjustment and realignment of certain modes of the operation as well as the equipment, taking a slightly different approach in the operational techniques for welding different alloys, and an increasing concern for absolute cleanliness. At Marshall Space Flight Center, a familiar statement was that "the weld may be defined as a continuous defect surrounded by parent metal." The high incidence of weld defects and high repair rates, even as late as 1967, was a continuing problem. One of the most frequent defects involved porosity. R. B. Hoppes described the situation in 1967: "In 144,000 inches [366 000 centimeters] of weld made on four Saturn V first stages, porosity accounted for 79% of the total number of defects. Cracks ranked second at 9%." The nagging problems were solved basically by the application of

some of the techniques and procedures outlined above, particularly cleanliness. Contaminants created most of the porosity problems, and Marshall engineers went back almost step by step through the welding process, rethinking their approach, and taking special care to eliminate any instance where contaminants might come into contact with the surfaces to be welded. It was only by this careful and conservative approach, rather than through some marvelous breakthrough, that the welding problems were finally surmounted.²⁵

Marshall's experience in solving welding problems, along with similar information from other NASA programs, was disseminated through a series of special publications by the NASA Technology Utilization program. Fourteen published studies, for example, were sponsored by MSFC through the Battelle Memorial Institute of Columbus, Ohio. The studies described the problems of weld porosity and defects and the various steps in welding the large-scale components that were part of the Saturn V development program.²⁶ Other NASA pamphlets resulting from the Apollo-Saturn program dealt with brazing and braze alloys, piping and tubing, seals and sealing, insulation tools and techniques, a technique for joining and sealing dissimilar metals, and the application of magnesium lithium alloys. The electromagnetic hammer developed in the S-IC manufacturing program was used by a number of aircraft and other metal-working firms, and the contributions of the Saturn program to general technology included a publication on advanced bearing designs. The commonplace, but highly useful, parade of developments and contributions ran the gamut from better adhesives for bonding auto trim to several different kinds of computer programming, to spray foam, to new types of pipe, and better ways of doing things in a wide variety of fields.²⁷

Saturn in Retrospect

There were numerous instances of new technological developments, some among the Saturn contractors, others involving both government and industry. The difficulties of Douglas in trying to find a good substitute for balsa wood in the S-IV and S-IVB stages is an example. North American took the lead in perfecting spray-foam insulation for the S-II second stage, including the special phenolic cutters to trim the stuff once it had cured. On the other hand, it is virtually impossible to pinpoint all the major technological innovations in Saturn, then ascribe them to personnel at Marshall or at some contractor's plant. Marshall set the specifications and guidelines, and the contractor produced the product. MSFC followed its contractors very closely, not only in paperwork, but also in hardware. Laboratories and test stands at Huntsville were not just backup facilities, they provided depth and additional manpower for problems encountered in a joint program. Thus the F-1 combustion

STAGES TO SATURN

instability problem was simultaneously tackled from several angles by both NASA and Rocketdyne. The Saturn program succeeded because complications were faced and resolved; the mutual goal was to make the vehicles work, and they did.

The whole field of cryogenics changed as a result of the Saturn program, with government and industry cooperating on a number of problems. For one thing, there was the sheer volume of production of cryogenic materials, storage, transportation, and many technical problems of piping it from one point to another at test sites and at the launch pad. Computer operations and related software were affected by the influence of Saturn requirements for test, checkout, and launch, which led, among other things, to the new computer language called ATOLL (Acceptance Test or Launch Language). Demands for unparalleled compactness and reliability in Saturn guidance and control resulted in instrument unit innovations such as unit logic devices and triple modular redundancy. As a part of the effort to keep weight at the minimum, guidance and control components in the instrument unit were fabricated from beryllium and magnesium-lithium alloys, the first application of these materials, which are difficult to work with, in the space program.

The unusually large dimensions of Saturn components posed recurrent complications. In developing the S-IC stage, production of the large skin panels depended on refinement of existing techniques of metals fabrication and forming, but even more in the manner and utilization of oversized tooling never accomplished before. In fact, in dealing with the technology of the Satellites in general, the most consistent factor seemed to be the enormous size of the vehicles. Time after time, when engineers and technicians were pressed to define what was "new" about the Saturn, what fantastic new technological techniques were applied in its development, personnel would shake their heads and invariably comment on size.²⁸ Size was a factor in tooling as well as in welding exotic space-age alloys, especially in the case of the S-II stage. Even though every attempt was made to use off-the-shelf hardware and existing technology, Saturn's size implied new requirements and new complications. It just was not possible, for example, to take an H-1 engine and easily upgrade it to the thrust of an F-1 engine. The extrapolation of existing technology simply did not work when the engines got into the operational regimes of higher flow rates, pressures, and the associated wear and tear on the engine machinery.

Saturn logistics generated unexpected difficulties. Prior to the Saturn program, rockets could be moved from factory to test site to launch pad by conventional means, such as available highway, water, or air transport. Saturn used these transport modes as well, but required oversized equipment, custom-built or modified for the job.

In terms of management, NASA seems to have borrowed, albeit with permutations, bits and pieces of managerial techniques from industry,

business, and the military. What NASA (and particularly Marshall Space Flight Center) apparently added was "visibility," in terms of progress and problems, as well as of the individual responsible for handling these aspects. Visibility, both for the product and for personnel, was the prime concern of the Program Control Center of Arthur Rudolph's Saturn V Program Office. Its success in tracking the myriad bits and pieces of Saturn vehicles impressed even NASA Administrator Webb, who prided himself on managerial techniques and skills. Claiming that MSFC was unusually thorough in its management may seem like a simplification. Given the diversity of the prime contractors and their armies of subcontractors and vendors, however, the clockwork efficiency and the reliability of the Saturn vehicles were remarkable. Meticulous attention to details, and keeping track of them, was a hallmark of MSFC.

It is worth noting that even after the Saturn V program was over, MSFC still received many requests from businesses and managers asking "how did you do it?" Here again it is probably wise to remember Bauer's admonition that space management, just like space hardware, has been frequently developed to meet particular and complex problems, not always compatible with the outside, or commercial, world.

In retrospect it seems that the impact of the Saturn program, in terms of spinoff, was best observed in improved industrial technique, in basic shop practices, and in the frequently prosaic but necessary areas of how to run machine tools, how to bend tubes, how to make and apply fasteners, and simply how to get around in a machine shop. This was part of Marshall's heritage anyhow. It must be remembered that the von Braun team came directly out of the Army tradition of the in-house arsenal philosophy, and that Marshall not only built the first of the Saturn I vehicles, but the first few S-IC first stages as well. Even though they did not get into the construction of S-II, S-IV, and S-IVB stages and their engines, Marshall consistently retained the in-house capability of duplicating test programs and even major parts of such hardware. As Lee James noted, it was difficult to make this kind of concept acceptable, and work effectively with the contractor. Marshall somehow carried it off.

The Apollo-Saturn program frequently used the overworked phrase, "government-industry team" in explaining how the Saturn program was carried out successfully. It would be easy to underestimate this phrase as a bit of public relations flak put out by the space centers as well as the manufacturers themselves. Such does not seem to be the case. It was not unusual, in the course of interviews with contractor and NASA personnel, to name someone who had been interviewed previously on a related topic. The mention would bring about a quick smile and a brightening of the eyes and a response like "Oh, do you know so and so? Yes, we worked on . . .," followed by one or two anecdotes indicating a feeling of exceedingly strong partnership. Government and contractor personnel actually did relate to each other, especially at the technical levels. This ingredient

STAGES TO SATURN

had to be important to the success of the program. It meant that individuals could easily call each other on the phone, discuss a problem, agree on a solution, and continue the work without major interruption.

The overall success of the Saturn program depended on a significant number of key decisions. One of these would have to be the decision in 1957 to start consideration of the clustered engine concept as a means to get heavy payloads into orbit. As natural as this concept seems today, it has to be remembered that the tricky nature and recalcitrant operating characteristics of rocket engines at that time suggested clustering of two or more engines would be courting absolute disaster. Next was the decision to use liquid hydrogen as one of the propellants. The application of this high-energy fuel made all the difference in the performance of the Saturn I, Saturn IB, and Saturn V vehicles. The use of the fuel allowed optimum sizing of the stages while keeping the weight to a minimum, so that a three-astronaut payload could be carried successfully into orbit and boosted into lunar trajectory. The controversy of EOR-LOR also stands out as a major period of decision early in the program. The choice of LOR led to the successful Saturn IB interim vehicle and stabilized the design configuration of the Saturn V. Finally, the decision to adopt the all-up concept stands out as one of the steps that permitted the United States to achieve the manned lunar landing on the moon before the end of the 1960s.

It is interesting to note that the von Braun team argued about the acceptance of three of these four major program milestones. On the other hand, the argument seems to have been one of degree rather than one of substance. Despite the strong recollections of individuals who say that von Braun opposed liquid hydrogen from the beginning, one must remember that LH₂ had been included very early by MFSC—in terms of the Centaur upper stage—in some of the early Saturn system studies.

The collective technological experience of the Saturn program was effectively applied in planning the Shuttle program, most notably in the Shuttle's propellant and propulsion systems. Marshall's experience in the handling and pumping of cryogenics, construction of fuel tanks, and development of the LH₂ engines were directly applied to the Shuttle concept.²⁹

In one respect, the technology of the Saturn vehicle represented the closing of a circle in international space partnership and cooperation. Allies in World War II, the U.S. and the U.S.S.R. both borrowed heavily from the technological storehouse of their defeated foe, Germany. In the early postwar years, both the U.S. and the U.S.S.R. learned from firing their respective stocks of captured V-2 rockets and perfected significant sectors of their own new rocket technology out of the V-2 experience common to both. This propulsion technology was further elaborated during the Cold War era along an escalating front of improved ICBM weaponry. When landing on the moon became an acknowledged race,

LEGACIES

both borrowed liberally from the extant technology of ICBM propulsion systems to build large rocket boosters. Tempered in wars both hot and cold, the technological heritage of the launch vehicles that put the Apollo-Soyuz Test Project into orbit could be traced back to the German technicians of World War II. The former wartime allies were now closing a technological circle that had ranged from partners, to protagonists, to partners again, with German expertise in rocketry as a catalyst.

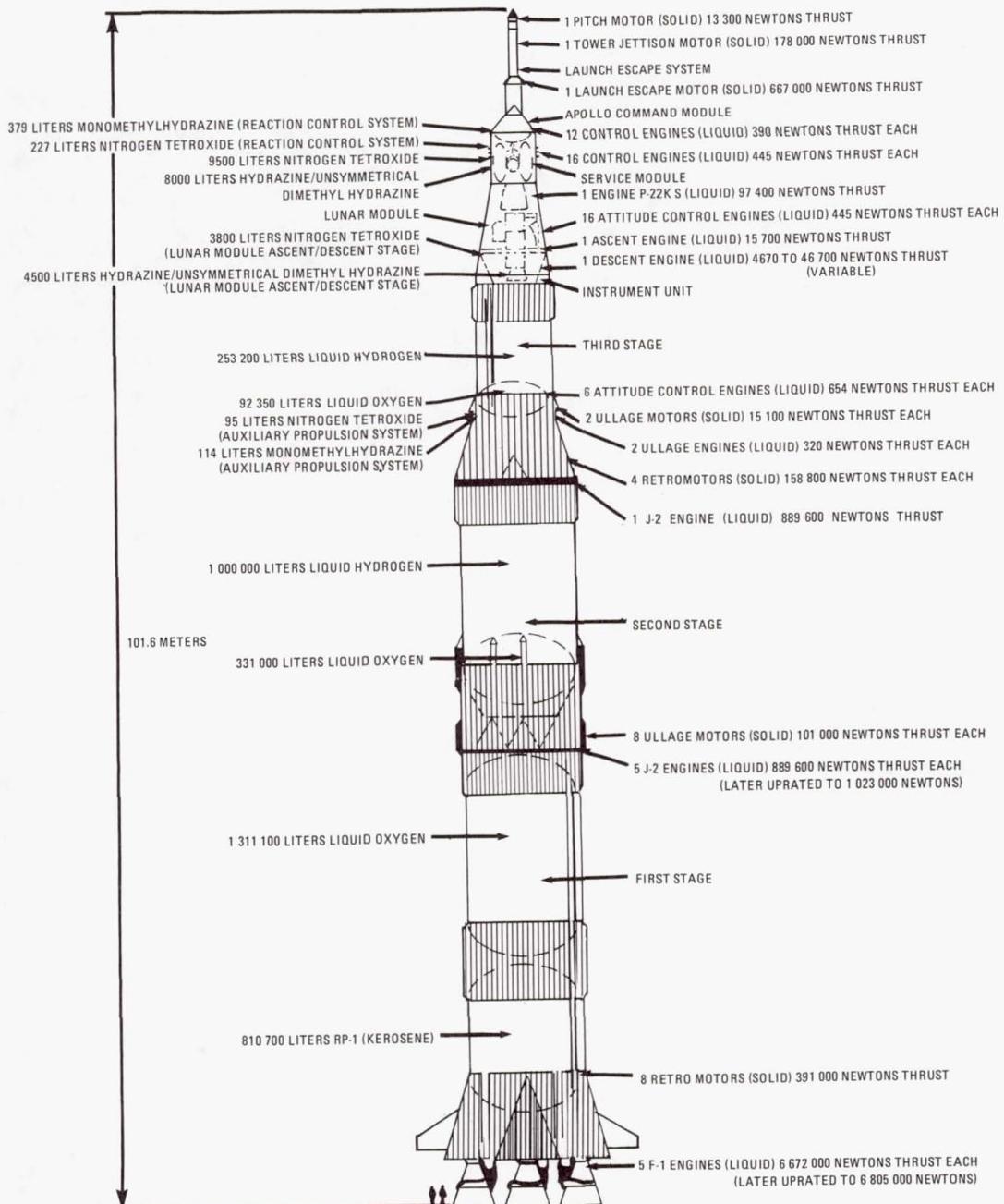
Partnership in space, by itself, will be no automatic guarantee of international amity. Partnership in space exploration may be an exhilarating prospect, however, offering an additional incentive for international cooperation and peace. If so, then the Saturn program may count this factor as its most important legacy.

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Appendices

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Appendix A—Schematic of Saturn V



APPENDIX A

Average R&D Costs for One Saturn I, IB, and V Launch Vehicle

Saturn I The initial development and production of the Saturn I was accomplished in-house; only the latter stages were placed on contract. Army projects assumed the initial FY 1958 and 1959 costs; NASA's total costs were not accumulated, during the development phase, to provide a true average unit cost (i.e., the original plan for S-I stages was to procure 21 each). At the conclusion of the program shown on the funding history, the total cost to NASA of the 10 Saturn Is actually launched was \$753 million.

Saturn IB and Saturn V

Costs for development and production of the Saturn IBs and Saturn Vs were not collected by specific vehicle because of the magnitude of the modifications based on mission requirements and because of the sustaining engineering and launch support required to support lengthened schedule restraints. The following unit costs include production of basic hardware plus modifications, spares, and associated ground support equipment for MSFC-responsible hardware only (first stage through instrument unit). Costs exclude all development, sustaining engineering, transportation, propellants, storage, etc., required to launch.

Stage	Basic Hardware Production	Modification Costs	Spares	Stage & Vehicle Ground Support Equipment (GSE)	GSE Systems Development	Total Stage
<i>Saturn IB Total Production Cost—\$46.7M</i>						
S-IB	7.9	0.3	1.1	0.1		9.4
S-IVB	13.0	1.9	0.9	0.2		16.0
IU	8.3	0.4	0.6	0.4		9.7
GSE	—	0.5	0.5	3.1	2.6	6.7
Engines	3.6	—	1.0	—		4.6
Total	32.8	3.1	4.1	3.8	2.6	46.4
<i>Saturn V Total Production Costs—\$113.1M</i>						
S-IC	19.4	0.2	1.4	0.3		21.3
S-II	21.0	1.0	3.6	0.6		26.2
S-IVB	15.6	0.2	1.2	0.3		17.3
IU	10.9	0.9	1.0	0.9		13.7
GSE			0.9	7.5	3.1	11.5
Engines	20.3		2.3	0.5		23.1
Total	87.2	2.3	10.4	10.1	3.1	113.1

Appendix B—Saturn V Prelaunch—Launch Sequence

AS-509 Prelaunch Operations

Event	Completed
LM Operations	30 Oct 70
Combined System Test	4 Dec 70
Unmanned Altitude Run	5 May 70
Manned Altitude Run	18 Sep 70
LM/SLA Mate	22 Oct 70
CSM Operations	3 Nov 70
Combined System Test	4 Dec 70
Unmanned Altitude Run	27 Aug 70
Manned Altitude Run	3 Sep 70
CSM/SLA Mate	31 Oct 70
Ordnance Installation	7 Nov 70
LV VAB Low Bay Operations	12 May 70
IU Low Bay Checkout	12 May 70
S-IVB Low Bay Checkout	12 May 70
S-II Low Bay Checkout	11 May 70
LV VAB High Bay Operations	29 Oct 70
S-IC Erection	14 Jan 70
LV Erection	13 May 70
LV Electrical System Test	6 Oct 70
LV Malfunction Overall Test	21 Oct 70
LV Service Arm Overall Test	29 Oct 70
Spacecraft Erection	4 Nov 70
Space Vehicle VAB Operations	8 Nov 70
Transfer to Pad	9 Nov 70
Pad Operations	31 Jan 70
LV Power ON	11 Nov 70
Space Vehicle Overall Test	7 Dec 70
LV Flight Systems Test	11 Dec 70
SV Flight Electrical Mating	11 Dec 70
SV Back-up Guidance Test	14 Dec 70
SV Flight Readiness Test	15 Dec 70
SV Hypergolic Loading	8 Jan 71
S-IC RP-1 Loading	9 Jan 71
CDDT-Wet/Dry	18 Jan 71
SV Countdown Prep.	25 Jan 72
Countdown	31 Jan 71

Typical Prelaunch Sequence
(Selected Events from T-9:30:00.0 to Liftoff)

Time before First Motion (HR:MIN:SEC)			Time before First Motion (HR:MIN:SEC)		
Start	Stop	Event	Start	Stop	Event
9:30:00.0	LIFTOFF	Switch LV Environmental Conditioning from Air to GN ₂	1:40:00.0	1:10:00.0	EDS Test
8:59:00.0	1:30:00.0	G&C System Checks	1:00:00.0	0:35:00.0	S-IC Fuel Level Adjust
8:59:00.0	LIFTOFF	ST-124M3 GN ₂ Sphere Pressurization	1:00:00.0	0:00:08.9	S-IVB Ambient GHe Supply Bottle Pressurization
8:59:00.0	1:00:00.0	S-IVB Ambient GHe Supply Bottle Prepressurization	0:57:00.0	0:47:00.0	Azimuth Laying
8:59:00.0	8:54:00.0	LVDC Sector Sum Check	0:51:30.0	LIFTOFF	Final CCS Checks
8:57:00.0	6:27:00.0	S-IC LOX Tank Purge (GN ₂)	0:51:25.0	0:46:25.0	Preflight Command System Test
8:34:00.0	7:39:00.0	S-II LOX Tank Prepressurization (GN ₂)	0:45:00.0	LIFTOFF	Final Tracking System Check
8:34:00.0	7:42:00.0	S-II LH ₂ Tank Purge (GHe)	0:43:00.0	0:05:00.0	CM Access Arm in Park Position
8:34:00.0	8:16:00.0	S-II LH ₂ Recirculation Line Purge (GHe)	0:42:00.0	LIFTOFF	LES Armed
8:15:00.0	8:00:00.0	S-IVB LOX Childdown Pump Cavity Purge	0:42:00.0	LIFTOFF	GNC System Checks
8:15:00.0	LIFTOFF	ST-124M3 System ON	0:42:00.0	0:37:00.0	IU Gimbal Checks
8:15:00.0		Start LV Cryogenic Loading	0:40:00.0	0:32:00.0	Range Safety Command Checks (Closed Loop)
8:00:00.0	7:55:00.0	Prepare to Launch Test	0:34:30.0	0:00:08.9	S-IVB Engine GHe Bottle Pressurization
8:00:00.0	LIFTOFF	IU Electrical Disconnect Purge	0:31:30.0	0:30:00.0	S-II LH ₂ Childdown Pump Test
8:00:00.0	7:40:00.0	S-II Turbine Start Bottle Purge (GHe)	0:31:30.0	0:30:00.0	S-IVB LOX/LH ₂ Childdown Pump Test
8:00:00.0	0:04:00.0	S-II Auxiliary Hydraulic Pump ON	0:30:00.0	0:26:00.0	Power Transfer Test
8:00:00.0	3:28:00.0	Operate DEE-3 System	0:25:00.0	LIFTOFF	Range Safety System ON
7:43:00.0	7:28:00.0	S-IVB LOX Tank Purge (GHe)	0:22:00.0	0:04:37.0	S-II Turbine Start Bottle Childdown (GH ₂)
7:42:00.0	4:54:00.0	S-II LH ₂ Tank Preconditioning	0:20:30.0	LIFTOFF	Final SV Telemetry System Checks
7:40:00.0	7:28:00.0	S-II Engine Turbopump Purge	0:20:00.0	0:14:30.0	S-IVB Turbine Start Bottle Purge
7:39:00.0	7:04:00.0	S-II LOX Tank Purge (GN ₂)	0:15:00.0	0:10:00.0	S-IVB Engine Thrust Chamber Purge
7:39:00.0	7:28:00.0	S-IVB J-2 Engine Turbopump Purge	0:14:30.0	0:05:30.0	S-IVB Turbine Start Bottle Childdown
7:31:00.0	4:11:00.0	S-IVB LH ₂ Tank Purge (GHe)	0:13:00.0	0:08:00.0	S-II Engine Thrust Chamber Purge (GHe)
7:28:00.0	7:13:00.0	S-II Engine Thrust Chamber Purge (GHe)	0:10:00.0	LIFTOFF	Prepare to Launch Test

SATURN V PRELAUNCH–LAUNCH SEQUENCE

7:28:00.0	7:24:00.0	S-IVB LOX Tank Precool (0-5%)	0:10:00.0	0:06:00.0	S-IC Fuel Jacket Topping (Glycol)
7:24:00.0	7:07:00.0	S-IVB LOX Tank Fast Fill (5-96%)	0:10:00.0	0:00:08.9	S-IVB Engine Thrust Chamber Chilldown
7:07:00.0	7:04:00.0	S-IVB LOX Tank Slow Fill (96-99%)	0:08:00.0	0:00:08.9	S-II Engine Thrust Chamber Chilldown
7:05:00.0	LIFTOFF	S-IC Engine Thrust Conditioning	0:05:30.0	LIFTOFF	S&A Devices Armed
7:05:00.0	6:30:00.0	IU CCS Checks	0:05:30.0	0:05:00.0	S-IVB Turbine Start Bottle Pressurization
7:04:00.0	6:54:00.0	S-II LOX Tank Precool (0-5%)	0:05:00.0	0:04:00.0	Remove Q-ball Cover
6:54:00.0	6:44:00.0	S-II LOX Tank Fast Fill (5-40%)	0:05:00.0	0:04:50.0	Retract and Lock CM Access Arm
6:44:00.0	6:30:00.0	S-II LOX Tank Fast Fill (40-96%)	0:04:37.0	0:03:07.0	S-II Turbine Start Bottle Pressurization
6:38:00.0	6:30:00.0	Preflight Command System Test, Houston	0:04:30.0	LIFTOFF	Terminal Countdown Sequencer Armed
6:30:00.0	6:27:00.0	S-II LOX Tank Slow Fill (96-99%)	0:03:07.0		Start Automatic Sequence
6:27:00.0	6:02:00.0	S-IC LOX Precool	0:03:07.0	0:00:30.0	S-II LOX Tank Prepressurization
6:02:00.0	5:45:00.0	S-IC LOX Tank Slow Fill (0-6.5%)	0:02:47.0	0:00:08.9	S-IVB LOX Tank Prepressurization
5:45:00.0	4:57:00.0	S-IC LOX Tank Fast Fill (6.5-98%)	0:01:37.0	0:00:04.1	S-IC Fuel Tank Prepressurization
5:45:00.0	0:03:06.0	S-II LOX Tank Replenish	0:01:37.0	0:00:30.0	S-II LH ₂ Tank Prepressurization
5:45:00.0	0:03:06.0	S-IVB LOX Tank Replenish	0:01:37.0	0:00:08.9	S-IVB LH ₂ Tank Prepressurization
4:57:00.0	0:00:08.9	S-IC GHe Supply Bottle Pressurization	0:01:37.0	LIFTOFF	S-IC LOX Tank Prepressurization
4:57:00.0	4:55:00.0	S-IC LOX Tank Slow Fill (98-100%)	0:00:50.0		Transfer to Internal Power
4:55:00.0	0:03:06.0	S-IC LOX Tank Replenish	0:00:40.0	LIFTOFF	S-IVB LH ₂ Vent Directional Control
4:54:00.0	4:36:00.0	S-II LH ₂ Precool (0-5%)	0:00:30.0		Flight Position ON
4:36:00.0	4:16:00.0	S-II LH ₂ Fast Fill (5-98%)	0:00:30.0	0:00:17.0	Retract and Lock S-IC Intertank Service Arm
4:16:00.0	4:11:00.0	S-II LH ₂ Slow Fill (98-100%)	0:00:30.0	LIFTOFF	S-IC Engine Hydraulic System Flight Activation
4:11:00.0	LIFTOFF	Q-Ball Power and Heaters ON	0:00:17.0	LIFTOFF	Guidance Reference Release
4:11:00.0	0:00:08.9	S-IVB LOX Tank GHe Supply Bottle Pressurization	0:00:16.2	0:00:11.0	Retract and Lock S-IC Forward Service Arm
4:11:00.0	3:58:00.0	S-IVB LH ₂ Precool (0-5%)	0:00:08.9	0:00:06.7	S-IC Ignition Command
3:58:00.0	3:33:00.0	S-IVB LH ₂ Fast Fill (5-98%)	0:00:05.3	LIFTOFF	Monitor S-IC Engine Thrust Buildup
3:33:00.0	3:28:00.0	S-IVB LH ₂ Slow Fill (98-100%)	0:00:01.0	LIFTOFF	Monitor Thrust OK AII S-IC Engines
3:33:00.0	0:03:06.0	S-II LH ₂ Replenish	0:00:01.0	0:00:00.0	Holddown Arm Release
3:28:00.0	0:03:06.0	S-IVB LH ₂ Replenish			
3:28:00.0	0:52:30.0	Astronaut Loading			

Typical Critical Event Sequence, First Opportunity TLI
(Event Times Are Based on AS-509 Launch Vehicle Operational Trajectory for 31 January 1971 Window, 72.067° Flight Azimuth)

Time from First Motion (HR:MIN:SEC)	Time from Reference (HR:MIN:SEC)	Event	Time from First Motion (HR:MIN:SEC)	Time from Reference (HR:MIN:SEC)	Event
-0:00:17.3	T ₁ -0:00:17.7	Guidance Reference Release	0:13:10.6	T ₅ +0:01:27.0	S-IVB APS Ullage Cutoff
0:00:00.0	T ₁ -0:00:00.4	First Motion	0:13:24.1	T ₅ +0:01:40.5	Begin Orbital Navigation
0:00:00.4	T ₁ +0:00:00.0	Liftoff			
0:00:01.4	T ₁ +0:00:01.0	Begin Tower Clearance Yaw Maneuver	2:21:00.1	T ₆ +0:00:00.0	Begin S-IVB Restart Preparations
0:00:09.4	T ₁ +0:00:09.0	End Yaw Maneuver	2:21:42.1	T ₆ +0:00:42.0	O ₂ H ₂ Burner (Helium Heater) On
0:00:12.3	T ₁ +0:00:11.9	Pitch and Roll Initiation	2:21:42.3	T ₆ +0:00:42.2	LH ₂ Continuous Vent Closed
0:01:09.0	T ₁ +0:01:08.6	Mach 1	2:29:16.4	T ₆ +0:08:16.3	S-IVB APS Ullage Ignition
0:01:25.5	T ₁ +0:01:25.1	Maximum Dynamic Pressure	2:29:16.9	T ₆ +0:08:16.8	Helium Heater Off
0:02:15.0	T ₁ +0:02:14.6	S-IC Center Engine Cutoff	2:30:30.1	T ₆ +0:09:30.0	Initiate J-2 Fuel Lead
			2:30:33.1	T ₆ +0:09:33.0	S-IVB APS Ullage Cutoff
0:02:15.1	T ₂ +0:00:00.0	Set Time Base 2	2:30:38.1	T ₆ +0:09:38.0	S-IVB Reignition (Start Tank Discharge Valve Opens)
0:02:42.8	T ₂ +0:02:27.7	Begin Tilt Arrest	2:30:40.6	T ₆ +0:09:40.5	S-IVB Engine at Mainstage
			2:33:55.6	T ₆ +0:11:55.5	MR Shift (First Opportunity Only)
0:02:44.8	T ₃ +0:00:00.0	S-IC Outboard Engine Cutoff	2:36:33.8	T ₇ -0:00:00.2	S-IVB Engine Cutoff, Second Burn
0:02:45.3	T ₃ +0:00:00.5	S-II Ullage Rocket Ignition			
0:02:45.5	T ₃ +0:00:00.7	Signal to Separation Devices and S-IC Rerorockets	2:36:34.0	T ₇ +0:00:00.0	Set Time Base 7
0:02:45.6	T ₃ +0:00:00.8	S-IC/S-II First Plane Separation Complete	2:36:34.5	T ₇ +0:00:00.5	LH ₂ Continuous Vent Open
0:02:46.2	T ₃ +0:00:01.4	S-II Engine Start Sequence Initiated	2:36:34.7	T ₇ +0:00:00.7	LOX Nonpropulsive Vent Open
0:02:47.2	T ₃ +0:00:02.4	S-II Ignition (Start Tank Discharge Valve Opens)	2:36:34.8	T ₇ +0:00:00.8	LH ₂ Nonpropulsive Vent Open
0:02:49.2	T ₃ +0:00:04.4	S-II Engines at Mainstage	2:36:37.6	T ₇ +0:00:03.6	Flight Control Coast Mode On
0:02:49.8	T ₃ +0:00:05.0	S-II Ullage Thrust Cutoff	2:36:39.0	T ₇ +0:00:05.0	Enable SC Control of LV
0:03:15.5	T ₃ +0:00:30.7	S-II Aft Interstage Drop (Second Plane Separation)	2:36:43.8	T ₇ +0:00:09.8	Translunar Injection
0:03:21.2	T ₃ +0:00:36.4	LET Jettison (Crew Action)	2:39:04.7	T ₇ +0:02:30.7	LOX Nonpropulsive Vent Closed
			2:39:04.9	T ₇ +0:02:30.9	LH ₂ Continuous Vent Closed
			2:39:04.9	T ₇ +0:02:30.9	Initiate Maneuver to and Maintain Local Horizontal Alignment (CSM Forward, Heads Down)

SATURN V PRELAUNCH-LAUNCH SEQUENCE

0:03:25.6	$T_3 + 0:00:40.8$	Initiate IGM	2:51:34.0	$T_7 + 0:15:00.0$	LH ₂ Nonpropulsive Vent Closed
0:07:43.8	$T_3 + 0:04:59.0$	S-II Center Engine Cutoff	2:51:34.0	$T_7 + 0:15:00.0$	Initiate Maneuver to and Maintain TD&E Attitude
0:07:52.2	$T_3 + 0:05:07.4$	MR Shift	3:01:34.0	$T_7 + 0:25:00.0$	CSM Separation (Variable)
0:09:16.67	$T_4 - 0:00:00.01$	S-II Outboard Engine Cutoff; Enable Chi Freeze	3:16:34.0	$T_7 + 0:40:00.0$	CSM/LM Docking (Variable)
0:09:16.68	$T_4 + 0:00:00.0$	Set Time Base 4; Begin Chi Freeze	3:36:34.4	$T_7 + 1:00:00.4$	LH ₂ Nonpropulsive Vent Open
0:09:17.6	$T_4 + 0:00:00.9$	S-IVB Ullage Ignition	3:51:34.0	$T_7 + 1:15:00.0$	LH ₂ Nonpropulsive Vent Closed
0:09:17.7	$T_4 + 0:00:01.0$	Signal to Separation Devices and S-II Retrorockets	3:56:34.0	$T_7 + 1:20:00.0$	SC/LV Final Separation (Variable)
0:09:17.8	$T_4 + 0:00:01.1$	S-II/S-IVB Separation	4:11:34.0	$T_7 + 1:35:00.0$ ($T_8 - 0:08:00.0$)	Initiate Maneuver to and Maintain S-IVB Evasive Attitude (Variable)
0:09:17.8	$T_4 + 0:00:01.1$	S-IVB Engine Start Sequence, First Burn	4:19:34.0	$T_8 + 0:00:00.0$	Set Time Base 8
0:09:20.8	$T_4 + 0:00:04.1$	S-IVB Ignition (Start Tank Discharge Valve Opens)	4:19:35.2	$T_8 + 0:00:01.2$	S-IVB APS Ullage Ignition
0:09:23.3	$T_4 + 0:00:06.6$	S-IVB Engine at Mainstage	4:20:55.2	$T_8 + 0:01:21.2$	S-IVB APS Ullage Cutoff
0:09:25.4	$T_4 + 0:00:08.7$	S-IVB Ullage Thrust End	4:29:14.2	$T_8 + 0:09:40.2$	Initiate Maneuver to and Maintain LOX Dump Attitude
0:09:26.1	$T_4 + 0:00:09.4$	End Chi Freeze	4:36:14.0	$T_8 + 0:16:40.0$	LH ₂ Continuous Vent Open
0:09:29.5	$T_4 + 0:00:12.8$	S-IVB Ullage Case Jettison	4:40:54.0	$T_8 + 0:21:20.0$	Start LOX Dump
0:11:35.6	$T_4 + 0:02:18.9$	Begin Chi Freeze	4:41:14.0	$T_8 + 0:21:40.0$	LH ₂ Continuous Vent Closed
0:11:43.4	$T_5 - 0:00:00.2$	S-IVB Cutoff, First Burn	4:41:42.0	$T_8 + 0:22:08.0$	End LOX Dump
0:11:43.6	$T_5 + 0:00:00.0$	Set Time Base 5	4:42:54.2	$T_8 + 0:23:20.2$	LOX Nonpropulsive Vent Open
0:11:43.9	$T_5 + 0:00:00.3$	S-IVB APS Ullage Ignition	4:42:59.0	$T_8 + 0:23:25.0$	LH ₂ Nonpropulsive Vent Open
0:11:53.4	$T_5 + 0:00:09.8$	Parking Orbit Insertion	5:59:34.0*	$T_8 + 1:40:00.0^*$	Initiate Maneuver to and Maintain S-IVB APS Impact Burn Attitude
0:12:03.6	$T_5 + 0:00:20.0$	Initiate Maneuver to and Maintain Local Horizontal Alignment (CSM Forward, Heads Down)	6:29:34.0*	$T_8 + 2:10:00.0^*$	S-IVB APS Ullage Ignition
0:12:03.7	$T_5 + 0:00:20.1$	Begin Orbital Guidance	6:33:35.0*	$T_8 + 2:14:01.0^*$	S-IVB APS Ullage Cutoff
0:12:42.6	$T_5 + 0:00:59.0$	LH ₂ Continuous Vent Open			

*Subject to update by DCS guidance commands to the LVDC after real-time assessment.

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Appendix C—Saturn Flight History

APPENDIX C

Saturn Family/Mission Data

Program	Launch Vehicle	Mission Desig	Launch Date	Payload	Description	Remarks
Saturn I	SA-1	—	10-27-61	Dummy	R&D, test S-1 stage propulsion, verify structure & aerodynamics	Objectives achieved
	SA-2	—	4-25-62	Water (95 tons)	R&D, observe water dispersion at high altitude	"Project Highwater" (release 22 900 gal water)
	SA-3	—	11-16-62	Water (95 tons)	R&D, observe water dispersion at high altitude	"Project Highwater" (release 22 900 gal water)
	SA-4	—	3-28-63	Dummy	R&D, demo engine-out capability (in-flt eng cutoff)	Objectives achieved
	SA-5	—	1-29-64	Dummy	R&D, 1st flt operation of S-IV second stage	First flt operations of S-IV second stage
	SA-6	—	5-28-64	BP-13	R&D, verify struct & aerodynamic design of Sat-I with Apollo boilerplate	Successful insertion into orbit following premature cutoff of one 1st stage engine
	SA-7	—	9-18-64	BP-15	R&D, demo of LES jettison	Active ST-124 guidance .
	SA-8	—	5-25-65	Pegasus 11 BP-26	Operational, meteoroid experiment near Earth environment	Successful 1st CCSD-built S-1 stage
	SA-9	—	2-16-65	Pegasus I BP-16	Operational, meteoroid experiment near Earth environment	Successful
	SA-10	—	7-30-65	Pegasus III BP-9	Operational, meteoroid experiment near Earth environment	Completed Saturn I program 2nd CCSD S-1 stage
Saturn IB	SA-201	AS-201	2-26-66	CSM-009	R&D, CSM subsys & struct integrity & veh compatibility	Reentry adequacy was demonstrated under Earth orbital conditions
	SA-202	AS-202	8-25-66	CSM-011	R&D, propulsion & entry control by G&N system	Demonstration of entry at 28 500 FPS
	SA-203	AS-203	7-5-66	LH ₂ in S-IVB	R&D, control of LH ₂ by continuous venting in orbit	Successful (4 orbits)
	SA-204	Apollo 5	1-22-68	LM-1	LM dev, verify ascent & descent prop sys eval LM staging	Successful (4 orbits)
	SA-205	Apollo 7	10-11-68	CSM-101	Operational, first manned CSM operation	163 orbits, off Earth duration 10 days & 20 hrs

SATURN FLIGHT HISTORY

Crew	Lunar Landing Site	Stages on Dock KSC					
		S-I	S-IV	S-IB	S-IU	S-IC	S-II
Unmanned	N/A	8-15-61	Dummy 8-15-61	—	8-15-61	—	—
Unmanned	N/A	2-27-62	Dummy 2-27-62	—	2-27-62	—	—
Unmanned	N/A	9-19-62	Dummy 9-19-62	—	9-19-62	—	—
Unmanned	N/A	2-2-63	2-2-63	—	2-2-63	—	—
Unmanned	N/A	8-21-63	9-21-63	—	8-21-63	—	—
Unmanned	N/A	2-18-64	2-22-64	—	2-18-64	—	—
Unmanned	N/A	6-7-64	6-12-64	—	6-7-64	—	—
Unmanned	N/A	2-28-65	2-25-65	—	3-8-65	—	—
Unmanned	N/A	10-30-64	10-22-64	—	10-30-64	—	—
Unmanned	N/A	6-1-65	5-8-65	—	6-1-65	—	—
Unmanned	N/A	8-14-65	—	8-14-65	10-22-65	—	—
Unmanned	N/A	2-7-66	—	2-7-66	2-21-66	—	—
Unmanned	N/A	4-12-66	—	4-12-66	4-14-66	—	—
Unmanned	N/A	8-15-66	—	8-15-66	8-16-66	—	—
Commander Schirra CM Pilot Eisele LM Pilot Cunningham	N/A	3-28-68	—	3-28-68	4-11-68	—	—
							4-7-68

APPENDIX C

Saturn Family Mission Data—Continued

Program	Launch Vehicle	Mission Desig	Launch Date	Payload	Description	Remarks
	SA-206	SL-2	5-25-73	CSM-116	First manned launch to the Earth orbiting space station. Repaired damaged solar array wing & deployed parasol	Duration 28 days
	SA-207	SL-3	7-23-73	CSM-117	Second manned launch to the Earth orbiting space station. Solar data, EREP, & biomedical experiments	Duration 59 days
Saturn IB	SA-208	SL-4	11-16-73	CSM-118	Third manned launch to the Earth orbiting space station. Solar data, EREP, & biomedical experiments	Duration 60 days Open-ended to 85 days
	SA-209	ASTP backup	—	CSM-119	Provided SL crew rescue capability until 2/8/74 (splashdown of SA-208)	SL mission successfully completed 2/8/74
	SA-210	ASTP	7-15-75	CSM-111	Conduct manned rendezvous and docking mission with U.S.S.R. (Soyuz)	—
	SA-211	Mission not assigned			—	—
	SA-501	Apollo 4	11-9-67	CSM-017 LTA-10R	R&D, launch veh & SC dev Sat veh performance	CM entry at lunar return velocity (three orbits)
	SA-502	Apollo 6	4-4-68	CSM-020 LTA-2R	R&D, demo of S-IC/ S-II & S-IVB separation	Eval of EDS closed-loop configuration (three orbits)
	SA-503	Apollo 8	12-21-68	CSM-103 LTA-B	Operational, first manned lunar orbital mission	20 hrs in lunar orbit (10 orbits). Off Earth duration 6 days & 3 hrs
Saturn V	SA-504	Apollo 9	3-3-69	CSM-104 LM-3	First manned CSM/LM oper demo lunar orbit rendezvous in Earth orbit	Off Earth duration 10 days & 1 hr (152 orbits)
	SA-505	Apollo 10	5-18-69	CSM-106 LM-4	First manned CSM/LM oper in cislunar & lunar environment	Simul lunar landing mission 61.6 hrs in lunar orbit (31 orbits). Off Earth duration 8 days
	SA-506	Apollo 11	7-16-69	CSM-107 LM-5 EASEP	First manned lunar landing mission development EASEP	One EVA 2.5 hrs, lunar stay 21.6 hrs. Off Earth duration 8 days & 3.3 hrs

SATURN FLIGHT HISTORY

Crew	Lunar Landing Site	Stages on Dock KSC					
		S-I	S-IV	S-IB	S-IU	S-IC	S-II
Commander Conrad							
Science Pilot Kerwin	N/A	—	—	8-22-72	8-24-72	—	—
Pilot Weitz							6-24-71
Commander Bean							
Science Pilot Garriot	N/A	—	—	3-30-73	6-12-73	—	—
Pilot Lousma							8-26-71
Commander Carr							
Science Pilot Gibson	N/A	—	—	6-20-73	5-9-73	—	—
Pilot Pogue							11-4-71
—	N/A	—	—	8-20-73	6-14-73	—	—
Commander Stafford							
CM Pilot Brand	N/A	—	—	4-22-74	5-14-74	—	—
DM Pilot Slayton							11-6-72
—	N/A	—	—	—	—	—	—
Unmanned	N/A	—	—	8-25-66	9-12-66	1-27-67	8-14-66
Unmanned	N/A	—	—	—	3-20-67	3-13-67	5-24-67
Commander Borman							
CM Pilot Lovell	N/A	—	—	—	1-4-68	12-27-67	12-24-67
LM Pilot Anders							12-30-67
Commander McDivitt							
CM Pilot Scott	N/A	—	—	—	9-30-68	9-30-68	5-15-68
LM Pilot Schweickart							9-12-68
Commander Stafford							
CM Pilot Young	N/A	—	—	—	12-15-68	11-27-68	12-10-68
LM Pilot Cernon							12-3-68
Commander Armstrong	Sea of Tranquility						
CM Pilot Collins	ret 21 kg	—	—	—	2-27-69	2-20-69	2-6-69
LM Pilot Aldrin	lunar samples						1-18-69

APPENDIX C

Saturn Family Mission Data — Continued

Program	Launch Vehicle	Mission Desig	Launch Date	Payload	Description	Remarks
	SA-507	Apollo 12	11-14-69	CSM-108 LM-6 ALSEP	Second manned lunar landing mission deploy ALSEP. Surveyor III investigation	Two dual EVAs 4 hrs & 3.75 hrs. Off Earth duration 10 days & 4.6 hrs
	SA-508	Apollo 13	4-11-70	CSM-109 LM-7 ALSEP	Mission aborted due to failure of SM oxygen storage sys. S-IVB impact on moon	LM lifeboat mode for lunar flyby & return to Earth. Off Earth duration 5 days & 22.9 hrs
	SA-509	Apollo 14	1-31-71	CSM-110 LM-8 ALSEP	Third manned lunar landing, deploy ALSEP lunar surface stay 33.5 hrs	Two dual EVAs 4.8 hrs & 4.3 hrs. Off Earth duration 9 days
Saturn V	SA-510	Apollo 15	7-26-71	CSM-112 LM-10 ALSEP LRV-1	Fourth manned lunar landing, deploy ALSEP 3 traverses with LRV-1 6.5 hrs - 7.2 hrs - 4.8 hrs	LRV traverses 27.9 km. Off Earth duration 12 days & 7.2 hrs
	SA-511	Apollo 16	4-16-72	CSM-113 LM-11 LRV-2 UV-photo	Fifth manned lunar landing deploy ALSEP-UV camera 3 traverses with LRV-2 7.2 hrs - 7.4 hrs - 5.6 hrs	LRV traverses 26.9 km. Off Earth duration 11 days & 2 hrs
	SA-512	Apollo 17	12-6-72	CSM-114, LM-12 LRV-3, ALSEP & surface expr.	Sixth manned lunar landing 3 traverses with LRV-3 7.2 hrs - 7.6 hrs - 7.3 hrs	LRV traverses distance 35.7 km
	SA-513	SL-1	5-14-73	Multidocking Adpt. ATM, Workshop Module Airlock	Unmanned launch placed space station in a circular Earth orbit 433 km	Manned logistics: launches SL-2, SL-3, & SL-4
	SA-514			Mission not assigned	—	—
	SA-515			Mission not assigned	—	—

SATURN FLIGHT HISTORY

Crew	Lunar Landing Site	Stages on Dock KSC						
		S-I	S-IV	S-IB	S-IU	S-IC	S-II	S-IVB
Commander Conrad	Ocean of Storms							
CM Pilot Gordon	ret 34 kg	—	—	—	5-8-69	5-3-69	4-21-69	3-9-69
LM Pilot Bean	lunar samples							
Commander Lovell	Lunar landing							
CM Pilot Swigert	aborted	—	—	—	7-7-69	6-16-69	6-29-69	6-13-69
LM Pilot Haise								
Commander Shepard	Fra Mauro							
CM Pilot Roosa	ret 43 kg	—	—	—	5-6-70	1-12-70	1-21-70	1-21-70
LM Pilot Mitchell	lunar samples							
Commander Scott	Hadley Appennines							
CM Pilot Worden	ret 77 kg	—	—	—	6-25-70	7-6-70	5-18-70	6-12-70
LM Pilot Irwin	lunar samples							
Commander Young	Descartes							
CM Pilot Mattingly	ret 97 kg	—	—	—	9-29-70	9-17-71	9-30-70	7-1-70
LM Pilot Duke	lunar samples							
Commander Cerman	Taurus Littrow							
CM Pilot Evans	ret 117 kg	—	—	—	6-20-72	5-11-72	10-27-70	12-21-70
LM Pilot Schmitt	lunar samples							
For crews refer to SA-206, 207, & 208	N/A	—	—	—	10-26-72	7-26-72	1-6-71	—
—	—	—	—	—	—	—	10-6-70	3-28-73
—	—	—	—	—	—	—	12-22-70	5-25-72

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Appendix D—Saturn R&D Funding History

Saturn R&D Funding History
(in \$ millions)

Fiscal Years	Army										NASA								NASA Run-Out Total		
	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76			
<i>Funding (Code)</i>																					
Saturn I (931)	20.6	64.3	97.4	191.4	254.5	177.7	32.0	0.2											838.1*		
Saturn IB (932)						18.3	140.0	258.7	248.7	194.0	101.1	42.1							1002.2		
Saturn V (933)						56.0	338.7	753.2	957.0	1105.2	1020.6	853.9	528.4	477.8	234.2	196.1	18.4		6539.5		
Engine Devel. (940)	10.0	23.8	77.7	103.9	135.1	166.0	166.3	133.2	49.8	20.5	7.1	6.7							900.1		
Launch Ops (950)						2.1	2.0												4.1		
& Sys Engr. (980)																					
Spacraft (Lunar Rover) (914)													0.2	0.3	19.3	18.9	0.7		39.4		
Total	30.6	88.1	175.1	353.4	748.6	1236.9	1413.3	1487.3	1264.4	975.7	577.9	503.8	253.1	196.8	18.4				9323.4		
<i>Costs</i>																					
Saturn I	7.4	32.4	59.8	101.8	246.5	320.3	65.3	5.1	0.3	-0.3	-0.1	-0.2	-0.1	-0.1					838.1		
Saturn IB						2.7	74.1	243.2	304.8	217.7	108.7	48.2	1.7	0.9	0.3	0.5	-0.1	-0.5	1002.2		
Saturn V						22.0	229.5	638.0	999.6	1174.8	1048.9	792.5	653.2	436.0	260.0	198.5	93.5	-5.9	-0.1	-1.0	6539.5
Engine Devel.	3.6	22.2	60.2	108.4	133.5	160.1	160.6	147.4	58.1	23.3	13.3	9.2	0.1	0.1					900.1		
Launch Ops/Sys Engr.						0.5	2.8	0.8											4.1		
Spacecraft (Lunar Rover)													16.8	21.2	1.2				39.4		
Total	11.0	54.6	120.0	232.2	612.7	1195.3	1469.5	1632.1	1325.0	924.2	714.6	463.5	282.1	200.0	94.0	-6.0	-0.6	-0.8	9323.4		

*Includes Army (pre-NASA) funding of \$84.9 million.

Note: Later-year credits result from final contract audits. Audit agency workload delays contract close-out several years in some cases.

Appendix E—Saturn V Contractors

Saturn V Subcontractors

The following are lists of subcontractors who played a major role in the development and production of the Saturn V launch vehicle. Many more subcontractors contributed to the total vehicle and program, but it is not practical to list them all.

Boeing Major Subcontractors

Subcontractor	Location	Product
Aeroquip Corp.	Jackson, Mich.	Couplings, pneumatic, and hydraulic hoses
Aircraft Products	Dallas, Tex.	Machined parts
AiResearch Manufacturing Co.	Phoenix, Ariz.	Valves
Applied Dynamics, Inc.	Ann Arbor, Mich.	Analog computers
Arrowhead Products, Div. of Federal-Mogul Corp.	Los Alamitos, Calif.	Ducts
The Bendix Corp., Pioneer-Central Div.	Davenport, Iowa	Loading systems and cutoff sensors
Bourns, Inc. Instrument Div.	Riverside, Calif.	Pressure transducers
Brown Engineering Co., Inc.	Lewisburg, Tenn.	Multiplexer equipment
The J. C. Carter Co.	Costa Mesa, Calif.	Solenoid valves
Consolidated Controls Corp.	Bethel, Conn. Los Angeles, Calif.	Pressure switches, transducers, and valves
The Eagle-Picher Co., Chemical and Metals Div.	Joplin, Mo.	Batteries
Electro Development Corp.	Seattle, Wash.	AC and DC amplifiers
Flexible Tubing Corp.	Anaheim, Calif.	Ducts
Flexonics, Div. of Calumet and Hecla, Inc.	Bartlett, Ill.	Ducts
General Precision, Inc. Link Ordnance Div.	Sunnyvale, Calif.	Propellant dispersion systems
Gulton Industries, C. G. Electronics Div.	Albuquerque, N. M.	Wiring boards

SATURN V SUBCONTRACTORS

Hayes International Corp.	Birmingham, Ala.	Auxiliary nitrogen supply units
Hydraulic Research and Manufacturing Co.	Burbank, Calif.	Servoactuators and filter manifolds
Johns-Manville Sales Corp.	Manville, N. J.	Insulation
Kinetics Corporation of California	Solano Beach, Calif.	Power transfer switches
Ling-Temco-Vought, Inc.	Dallas, Tex.	Skins, emergency drains, and heat shield curtains
Marotta Valve Corp.	Boonton, N. J.	Valves
Martin Marietta Corp.	Baltimore, Md.	Helium bottles
Moog, Inc.	East Aurora, N. Y.	Servoactuators
Navan Products, Inc.	El Segundo, Calif.	Seals
Parker Aircraft Co.	Los Angeles, Calif.	Valves
Parker Seal Co.	Culver City, Calif.	Seals
Parsons Corp.	Traverse City, Mich.	Tunnel assemblies
Precision Sheet Metal Inc.	Los Angeles, Calif.	Filter screens, anti-vortex, and adapter assemblies
Purolator Products, Inc., Western Div.	Newbury Park, Calif.	Umbilical couplings
Kandall Engineering Co.	Los Angeles, Calif.	Valves
Raytheon Co.	Waltham, Mass.	Cathode ray tube display system
Rohr Corp.	Chula Vista, Calif.	Heat shields
Servonic Instruments, Inc.	Costa Mesa, Calif.	Pressure transducers
Solar, Division of International Harvester	San Diego, Calif.	Ducts
Southwestern Industries, Inc.	Los Angeles, Calif.	Calips pressure switches
Space Craft, Inc.	Huntsville, Ala.	Converters
Stainless Steel Products, Inc.	Burbank, Calif.	Ducts
Standard Controls, Inc.	Seattle, Wash.	Pressure transducers
Statham Instruments, Inc.	Los Angeles, Calif.	Pressure transducers

Boeing Major Subcontractors — Continued

Subcontractor	Location	Product
Sterer Engineering and Manufacturing Co.	Los Angeles, Calif.	Valves
Stresskin Products Co.	Costa Mesa, Calif.	Insulation
Systron-Donner Corp.	Concord, Calif.	Servo accelerometers
Thiokol Chemical Corp., Elkton Div.	Elkton, Md.	Retrorockets
Trans-Sonics, Inc.	Burlington, Mass.	Measuring systems and thermometers
Unidynamics/St. Louis, A Division of UMC Industries, Inc.	St. Louis, Mo.	Spools, harnesses, and ducts
United Control Corp.	Redmond, Wash.	Ordnance devices and control assemblies
Vacco Industries	South El Monte, Calif.	Filters, relief valves, and regulators
Whittaker Corp.	Chatsworth, Calif.	Valves and gyros
Fred D. Wright Co., Inc.	Nashville, Tenn.	Support assemblies and measuring racks

Douglas Major Subcontractors

Subcontractor	Location	Product
Accessory Products Co., Div. of Textron, Inc.	Whittier, Calif.	Valves/heaters
Aeroquip Corp., Marman Div.	Los Angeles, Calif.	Clamps
Airdrome Parts Co.	Inglewood, Calif.	Fittings
AiResearch Mfg. of Ariz.	Phoenix, Ariz.	Valves
Airtex Dynamics, Inc.	Compton, Calif.	Tank assemblies
Amco Engineering Co.	Chicago, Ill.	Cabinets
American Electronics, Inc.	Fullerton, Calif.	Batteries
Amp, Inc.	Harrisburg, Pa.	Electrical panels
Ampex, Corp.	Los Angeles, Calif.	Tape recorders

SATURN V SUBCONTRACTORS

Amphenol Borg Electronics Corp.	Chicago, Ill.	Connectors
Anaconda Metal Hose Div.	Waterbury, Conn.	Metal hose
Astrodata, Inc.	Anaheim, Calif.	Telemetry
Avnet Corp.	Westbury, L. I., N. Y.	Electrical connectors
Barry Controls	Watertown, Mass.	Electronic controls
Bertea Products	Pasadena, Calif.	Transmitter, fabricated assemblies
Brown Engineering Co., Inc.	Huntsville, Ala.	Telemetry equipment
Calmech Mfg. Co.	Los Angeles, Calif.	Valves
Capital Westward, Inc.	Paramount, Calif.	Filters
Christie Electric Corp.	Los Angeles, Calif.	Meters
Consolidated Electrodynamics	New York, N. Y.	Electronic equipment
Data Sensors	Gardena, Calif.	Transducers
Deutsch	Los Angeles, Calif.	Fittings
Dynatronics, Inc.	Orlando, Fla.	Telemetry equipment
Eagle-Picher Co.	Joplin, Mo.	Batteries
Electra Scientific Corp.	Fullerton, Calif.	Transducers
Electrada Corp.	Culver City, Calif.	Electrical components
Fairchild Camera Inst. Corp.	Plainview, L. I., N. Y.	Cameras, oscilloscopes
Fairchild Controls Div.	Montebello, Calif.	Valves
Fairchild Hiller Corp.	Bayshore, L. I., N. Y.	Valves
Fairchild Semiconductor	Hollywood, Calif.	Semiconductors
Fairchild Stratos	Bayshore, L. I., N. Y.	Valves
Flexible Metal Hose Mfg. Co.	Costa Mesa, Calif.	Metal hose
	Northridge, Calif.	

Douglas Major Subcontractors — Continued

Subcontractor	Location	Product
Flomatics, Inc.	Natoma, Calif.	Valves
Frebank Co.	Glendale, Calif.	Switches
Control Data Corp.	Minneapolis, Minn.	Computers
General Electric Co.	Waterford, N. Y.	Electrical components
Giannini Controls Corp.	Durate/Pasadena, Calif.	Transducers
Grove Valve Regulator Co.	El Segundo/Oakland, Calif.	Valves
Hadley, B. H. Co.	Pomona, Calif.	Relays
Hewlett Packard Co.	Pasadena, Calif.	Oscilloscopes/recorder
Hexcel Products, Inc.	Berkeley, Calif.	Honeycomb panels
Honeywell, Inc.	Minneapolis, Minn.	Temperature controls, gyros, sensors
ITT Wire and Cable	Clinton, Mass.	Wire and cable
K-Tronics	Los Angeles, Calif.	Semiconductors
Kaiser Aluminum Chemical Sales, Inc.	Spokane, Wash. Halethorpe, Md.	Raw material, cable
Kinetics, Corp.	Solano Beach, Calif.	Electronic equipment
Ladewig Valve	Los Angeles, Calif.	Valves
Lanagan, W. M. Co., Inc.	Costa Mesa, Calif.	Valves
Leonard, Wallace O., Inc.	Pasadena, Calif.	Valves
Linde Co., Div. Union Carbide	El Monte, Calif.	Batteries
Litton Industries of Calif.	Beverly Hills, Calif.	Transducers
Magnesium Alloy Prods. Co.	Compton, Calif.	Castings
Magnetika, Inc.	Venice, Calif.	Batteries
Marotta Valve Corp.	Santa Ana, Calif.	Valves

SATURN V SUBCONTRACTORS

Marshall, G. S. Co.	San Marino, Calif.	Electronic hardware
Mason Electric Div. Ansul.	Los Angeles, Calif.	Switches
Master Specialties Co.	Los Angeles, Calif.	Meters
Menasco Mfg. Co.	Burbank, Calif.	Fabricated assemblies
Military Products Div., Clary	San Gabriel, Calif.	Electrical fittings
Moog Servo Controls, Inc.	Aurora, N. Y.	Valves
Motorola Semiconductor Products	Hollywood, Calif.	Semiconductors
Pacific Valve, Inc.	Long Beach, Calif.	Valves
Parker Aircraft Co.	Los Angeles, Calif.	Fittings/valves
Pesco Products Div., Borg Warner	Bedford, Ohio	Pumps
Philco Corp.	Philadelphia, Pa.	Radio equipment
Planautics Corp.	Solano Beach, Calif.	Switches
Potter Brumfield	Princeton, Ind.	Switches, relays
Purolator Products, Inc., Western Div.	Van Nuys, Calif.	Filters
Reynolds Metals Co.	Birmingham, Ala.	Raw material (aluminum)
Rosemount Eng. Co.	Minneapolis, Minn.	Temperature controls
Sandorn Co.	Waltham, Mass.	Recorders
Scintilla Div. Bendix	Sidney, N. Y.	Electrical connectors
Sealol Corp.	Providence, R. I.	Valves
Servonic Instruments, Inc.	Costa Mesa, Calif.	Transducers
Signet Scientific	Burbank, Calif.	Ovens
Snap Tite	Union City, Pa.	Connectors
Sperry Gyro Co. Div., Sperry Rand	Great Neck, L. I., N. Y.	Instruments
Stainless Steel Products	Burbank, Calif.	Flexible ducts

Douglas Major Subcontractors — Continued

Subcontractor	Location	Product
Statham Instruments, Inc.	Los Angeles, Calif.	Transducers
TRW, Inc.	Cleveland, Ohio	Attitude control rocket engines
Trans-Sonics, Inc.	Lexington, Mass.	Temperature controls
Technology Instruments Corp.	Newbury Park, Calif.	Potentiometers
Telemetrics, Inc., Subsidiary of Arnoux Corp.	Santa Ana, Calif.	Ground support electronics
Texas Instruments, Inc.	Dallas, Tex.	Resistors/transistors
U. S. Steel Corp. U. S. Steel, Supply Div.	Seattle, Wash.	Raw material
Vacco Valve Company	El Monte, Calif.	Valves
Vickers	Detroit, Mich.	Pumps
Vinson Mfg. Co., Inc.	Van Nuys, Calif.	Valves
W & S Industries	El Monte, Calif.	Connectors
Winsco Instruments Control	Santa Monica, Calif.	Temperature control units
Wyman Gordon Co.	Worcester, Mass.	Forgings

IBM Major Subcontractors

Subcontractor	Location	Product
Aerodyne Controls Corp.	Farmingdale, N. Y.	First stage regulator, gas bearing pressure regulator
Airtek Div., Fansteel Metallurgical Corp.	Compton, Calif.	2-cubic-foot bottle 165-cubic-inch sphere
Applied Microwave Laboratory, Inc.	Andover, Mass.	T/M power divider
Astro Space Laboratories, Inc.	Huntsville, Ala.	Bleeder assembly Union orifice assembly
Automatic Metal Products Corp.	Brooklyn, N. Y.	Coaxial switch

SATURN V SUBCONTRACTORS

AVCO Corp.	Nashville, Tenn. Huntsville, Ala.	Cable trays Gas bearing mounting panel Measuring range cards Measuring range cards software Thermal conditioning panels
Avion Electronics, Inc.	Paramus, N. J.	Telemetry directional coupler VSWR measuring assembly
Bourns, Inc.	Riverside, Calif.	Transducer pressure gauges
Brown Engineering Co., Inc.	Huntsville, Ala.	Acquisition system Alternating current amplifier assembly Measuring rack selector Measuring rack assembly Mod 145 multiplexers Mod 245 multiplexers Mod 270 multiplexers Pulse code modulated digital data Radio frequency analog Radio frequency pulse code modulated Telemetry assembly A3 Telemetry assembly B1 Telemetry assembly SSB Telemetry calibrators Telemetry pulse code
Chrysler Corp.	Huntsville, Ala.	Q-ball Vehicle plate assembly
Conic Corp.	San Diego, Calif.	UHF transmitter
Cox Instruments Div., Lynch Corp.	Detroit, Mich.	Flowmeters
Eagle-Picher Industries, Inc.	Joplin, Mo.	Primary battery

IBM Major Subcontractors — Continued

Subcontractor	Location	Product
Electro Development Corp.	Seattle, Wash.	Amplifier direct current Channel selector A Channel selector B
Electronic Communications, Inc.	St. Petersburg, Fla.	Control computer
EIMAC Div., Varian	San Carlos, Calif.	UHF transmitter
The Foxboro Co.	Foxboro, Mass.	Gas temperature probe
Fenwall Electronics, Inc.	Framingham, Mass.	Temperature gauges
Flodyne Controls, Inc.	Linden, N. J.	Shut-off ball valve
Gulton Industries, Inc.	Hawthorne, Calif.	Electrical cables Vibration accelerometers 5-volt power supply
Hamilton-Standard Div., United Aircraft Corp.	Windsor Locks, Conn.	Preflight heat exchanger
Hayes International Corp.	Huntsville, Ala.	Network cables
Hydro-Aire Div., Crane	Burbank, Calif.	Coolant pump, R&D
ITT Wire and Cable Div., International Telephone and Telegraph Corp.	Clinton, Mass.	Wire Cables Coaxial cables
Marotta Valve Corp.	Boonton, N. J.	Shut-off valve Solenoid valve
Martin Co.	Orlando, Fla.	Control signal processor

SATURN V SUBCONTRACTORS

Melpar, Inc.	Falls Church, Va.	C-band antenna Command antenna Command directional coupler Command power divider Telemetry antenna Telemetry power divider
Motorola, Inc.	Scottsdale, Ariz.	C-band transponder Command receiver
North American Aviation, Inc.	Tulsa, Okla.	Structure segments
Nortronics Div., Northrop Corp.	Norwood, Mass.	Rate gyro package
Ralph M. Parsons Electronics Corp.	Pasadena, Calif.	Tape recorder
Perkin-Elmer Corp.	Norwalk, Conn.	Retroreflector
Potter Aeronautical Corp.	Union, N. J.	2 flowmeters
Purolator Products, Inc.	Los Angeles, Calif.	Gas bearing pressure regulator Quick disconnect coupling
Rantec Corp.	Calabasas, Calif.	Telemetry RF coupler
Raytheon Co.	Bristol, Tenn.	AZUSA antenna
Resistoflex Corp.	Roseland, N. J.	Flex hose assembly
Rosemount Engineering Co.	Minneapolis, Minn.	2 temperature gauges
Servonic Instruments, Inc.	Costa Mesa, Calif.	2 transducer pressures
Sierra Electronics Div., Philco-Ford Corp.	Menlo Park, Calif.	Coaxial terminal
Solar Div., International Harvester Co.	San Diego, Calif.	Gas bearing heat exchanger Manifold assembly Water methanol accumulator

IBM Major Subcontractors — Continued

Subcontractor	Location	Product
Space Craft, Inc.	Huntsville, Ala.	CIU 501 Command decode Frequency DC converter 2 multiplexers 410 Servoaccelerometer unit
Spaco, Inc.	Huntsville, Ala.	2 servoaccelerometer units
Statham Instruments, Inc.	Los Angeles, Calif.	Control accelerometer
Systron-Donner Corp.	Concord, Calif.	2 force balance accelerometers
Tavco, Inc.	Santa Monica, Calif.	Pressure switch
Teledyne Precision, Inc.	Hawthorne, Calif.	Thermal probes
Transco Products, Inc.	Venice, Calif.	CCS coaxial switch
TRW, Inc.	Cleveland, Ohio	Coolant pump
United Control Corp.	Redmond, Wash.	Temperature control assembly
Vacco Industries	South El Monte, Calif.	Filter Quality test filter
Watkins-Johnson Co.	Palo Alto, Calif.	Power amplifier
Wyle Laboratories	Huntsville, Ala.	Component testing Structure testing

North American Space Division Major Subcontractors

Subcontractor	Location	Product
Acoustica Associates	Los Angeles, Calif.	Transducers
American Brake Shoe Co.	Oxnard, Calif.	Hydraulic pumps
Amp, Inc.	Hawthorne, Calif.	Patch panels

Amphenol Space & Missile Systems Div., Amphenol-Borg Electronics Corp.	Chatsworth, Calif.	Patch panels
Astrodata, Inc.	Anaheim, Calif.	Time code generator Digital multimeter
Babcock Relay, Division of Babcock Electronics	Costa Mesa, Calif.	Relays Generator
Barry Controls	Glendale, Calif.	Shock mounts
Boonshaft and Fuchs, Division of Weston	Monterey Park, Calif.	Servoanalyzer
Computer Measurements	San Fernando, Calif.	Counters
Consolidated Electrodynamics Corp.	Pasadena, Calif.	Tape recorder
Deutsch Co., Electronic Components Division	Banning, Calif.	Connectors
Electrada Corp.	Culver City, Calif.	Test conductor console
Electronic Specialty Co.	Los Angeles, Calif.	Hybrid junction, band pass, filter, low pass filter
Electroplex, Subsidiary Borg-Warner Corp.	Santa Ana, Calif.	Logic modules Power supplies Cryogenic lines
Fairchild Precision Metal Products, Division of Fairchild Camera and Instrument	El Cajon, Calif.	
B. H. Hadley (Royal Industries)	Pomona, Calif.	Disconnects
Hallicrafters Pacific Division	Santa Ana, Calif.	Power supply
W. O. Leonard, Inc.	Pasadena, Calif.	Vent valves
Micro-Radionics, Inc.	Van Nuys, Calif.	RF couplers
Non-Linear Systems, Inc.	So. Pasadena, Calif.	Scanners
Parker Aircraft Co.	Los Angeles, Calif.	Hydraulic systems

North American Space Division Major Subcontractors — Continued

Subcontractor	Location	Product
Rantec Corp.	Calabasas, Calif.	Mistram antenna Mistram coupler Multiplexer
Rocketdyne Div., North American Aviation	McGregor, Tex.	Ullage rocket motors
Servonic Instruments, Inc.	Costa Mesa, Calif.	Transducers
Solar Division, International Harvester Corp.	San Diego, Calif.	Cryogenic lines
Stainless Steel Products	Burbank, Calif.	Cryogenic lines
Transco Products, Inc.	Venice, Calif.	Power dividers
United Electrodynamics, Inc.	Pomona, Calif.	PCM RF assemblies

North American Rocketdyne Major Subcontractors

Subcontractor	Location	Product
A&M Castings Inc.	South Gate, Calif.	Aluminum castings
Ace Industries	Santa Fe Springs, Calif.	Machined assemblies, nozzles, rotors, stators, and brg. supports
Adept Mfg. Co.	Los Angeles, Calif.	Inducers
Amphenol Corp.	Broadview, Ill.	Connectors
Anaconda Metal Hose	Los Angeles, Calif.	Flex hoses
Anaconda Amer. Brass Co.	Detroit, Mich.	OFHC copper
Arcee Foundry	Norwalk, Calif.	Castings
Arcturus Mfg. Co.	Oxnard, Calif.	Forgings
Bendix Corp., Scintilla Div.	Sidney, N. Y.	Connectors
Beuhler Corp., Indiana Gear Wks.	Indianapolis, Ind.	Gears and shafts

SATURN V SUBCONTRACTORS

Borg Warner Corp., Borg Warner Mech. Seals Div.	Vernon, Calif.	Seals
Calif. Doran Heat Treating Co.	Los Angeles, Calif.	Thermal processing of various major engine components
Cam Car Company	Rockford, Ill.	RD bolts
Chicago Rawhide Co.	Chicago, Ill.	Seals
Cleveland Graphite Bronze Div., Clevite Corp.	Cleveland, Ohio	Seals
Consolidated Electrodynamics Corp.	Pasadena, Calif.	Connectors and transducers
Aerospace Div., DK Mfg. Co.	Batavia, Ill.	Flex lines, bellows, and gimbals
Fairchild Metal Products Div., Fairchild Camera & Instru.	El Cajon Calif.	Bellows, ducts, gimbals, and line assemblies
General Labs, Inc.	Norwich, N. Y.	Exciters and igniters
Globe Aerospace	North Hollywood, Calif.	Machined metal parts, fittings, and elbows
Herlo Engineering Corp.	Hawthorne, Calif.	Major machined components
Hollywood Plastics, Inc.	Los Angeles, Calif.	ABS Royalite closures, covers, and other protective devices
Howmet Corp., Austenal Div.	Dover, N. J.	Castings
Huntington Alloys, International Nickel Co.	Huntington, W. Va.	Inco sheet and plate
Industrial Tectonics, Inc.	Burbank, Calif.	Actuators, brgs.
General Controls, Inc.	Louisville, Ky.	Honeycomb
Kentucky Metals	Sun Valley, Calif.	Valves
L. A. Gauge Co., Inc.	San Diego, Calif.	Seals, gimbals, machined assemblies
Langley Corp.	Santa Fe Springs, Calif.	Tubing—thrust chamber
LeFiell Mfg. Co.	Rockaway, N. J.	Forgings
McWilliams Forge Co.		

North American Rocketdyne Major Subcontractors — Continued

Subcontractor	Location	Product
Orbit Machine Corp.	Gardena, Calif.	Seals
Parker Seal Company	Culver City, Calif.	O-Rings, seals, and orifice plates
Paragon Die Tool & Engr.	Pacoima, Calif.	Stators, brg. supports
Precision Sheet Metal, Inc.	Los Angeles, Calif.	Major sheet metal subassemblies, jackets
Quadrant Engr. Company	Gardena, Calif.	Valves and components
Reisner Metals, Inc.	South Gate, Calif.	Forgings
Rohr Corp.	Chula Vista, Calif.	Major sheet metal subassemblies
Rosemount Engr. Co.	Minneapolis, Minn.	Pressure and temperature transducers
Scientific Data Systems	Pomona, Calif.	Circuit boards
Southwestern Industries	Los Angeles, Calif.	Switches
Solar, Div. of International Harvester Co.	San Diego, Calif.	Valves
Statham Instruments	Los Angeles, Calif.	Transducers, connectors, electronic assemblies
Standard Pressed Steel	Santa Ana, Calif. & Jenkinstown, Pa.	RD bolts
Texas Instruments	Dallas, Tex.	Transistors
Turbo Cast Inc.	Los Angeles, Calif.	Castings
Union Carbide Corp., Haynes Stellite Div.	Kokomo, Ind.	Castings, Hastelloy C, Rene 41
Viking Forge & Steel Co.	Albany, Calif.	Forgings
Western Arc Welding Co.	Los Angeles, Calif.	Welded assemblies
Western Way Inc.	Van Nuys, Calif.	Ducts, line assemblies, heat exchangers
Winsco Instruments & Controls	Santa Monica, Calif.	Transducer and receptacles, temperature and pressure transducers
Wyman-Gordon Company	N. Grafton, Mass.	Forgings

Appendix F—Location of Remaining Saturn Hardware

Location of Remaining Saturn Hardware
(As of 5 June 1975)

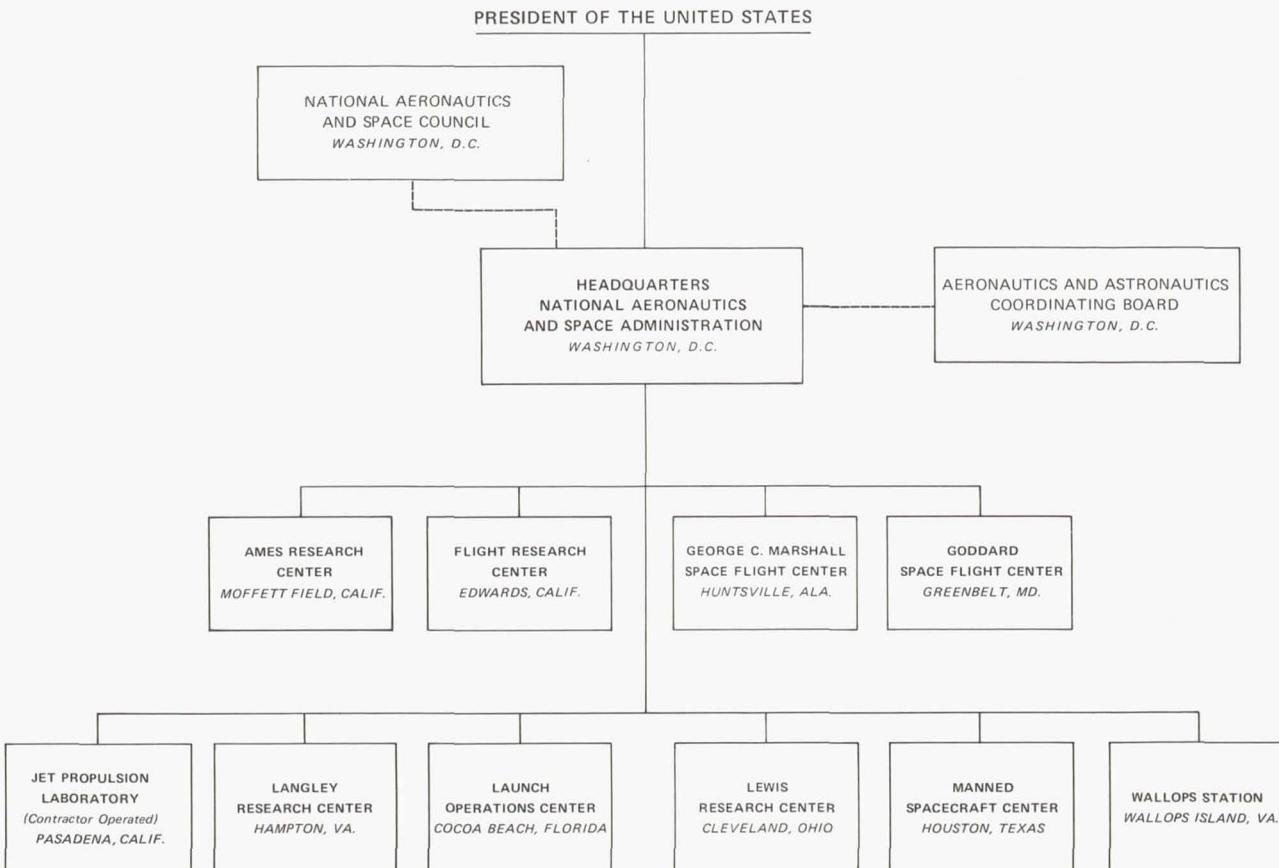
<hr/> Saturn V <hr/>				
Vehicle Number	S-IC Stage	S-II Stage	S-IVB Stage	IU
SA 513 (Skylab I)			KSC	
SA 514	MAF	KSC	KSC	MSFC
SA 515	MAF	KSC	MSFC (used for Skylab backup workshop)	MSFC

<hr/> Saturn IB <hr/>				
Vehicle Number	S-IB Stage	S-IVB Stage	IU	
SA 209 (ASTP backup)	KSC	KSC	KSC	
SA 211	MAF	KSC	MSFC	
SA 212	KSC	(used on SA 513)	MSFC	for disposal
SA 213	MAF	declared surplus, stripped		
SA 214	MAF	and placed on lot		

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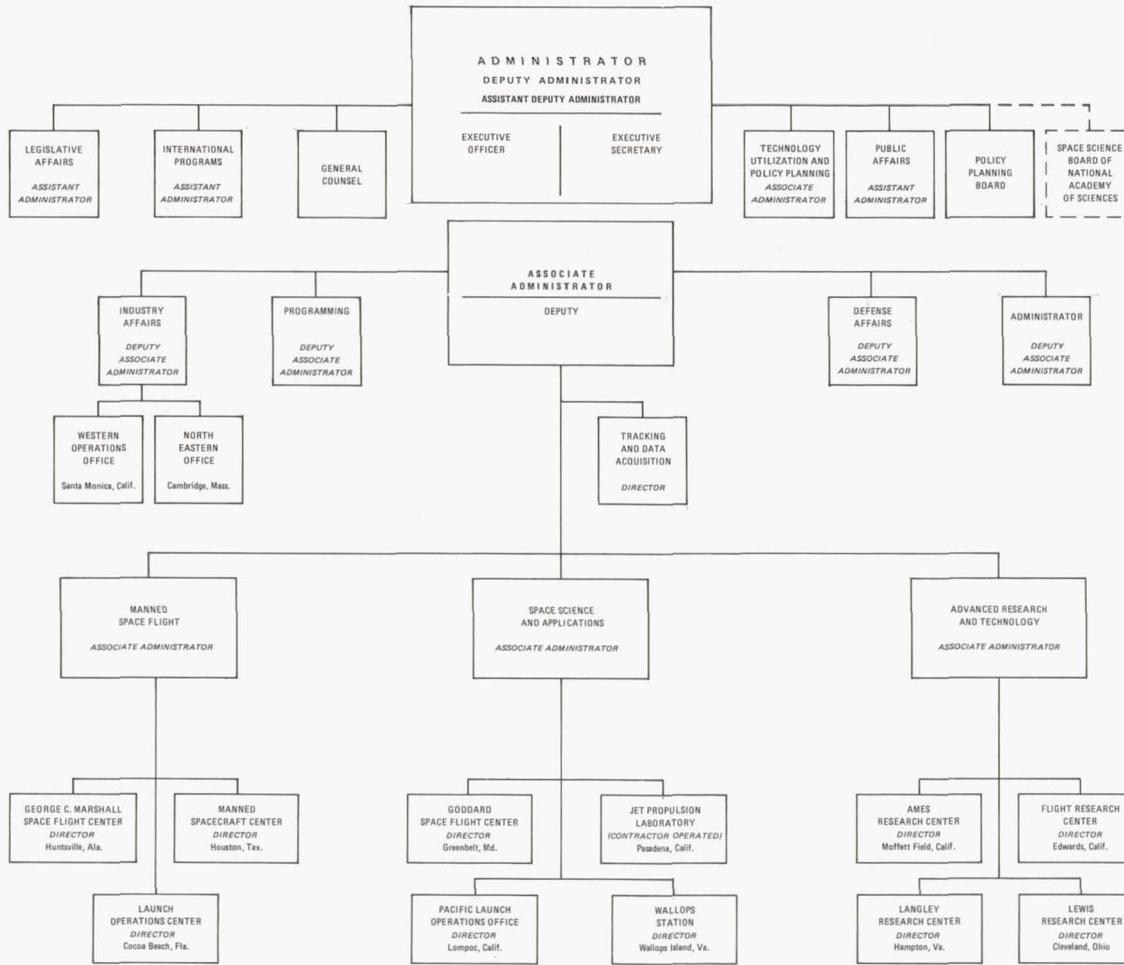
Appendix G—NASA Organization During Apollo-Saturn

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
(April 1963)

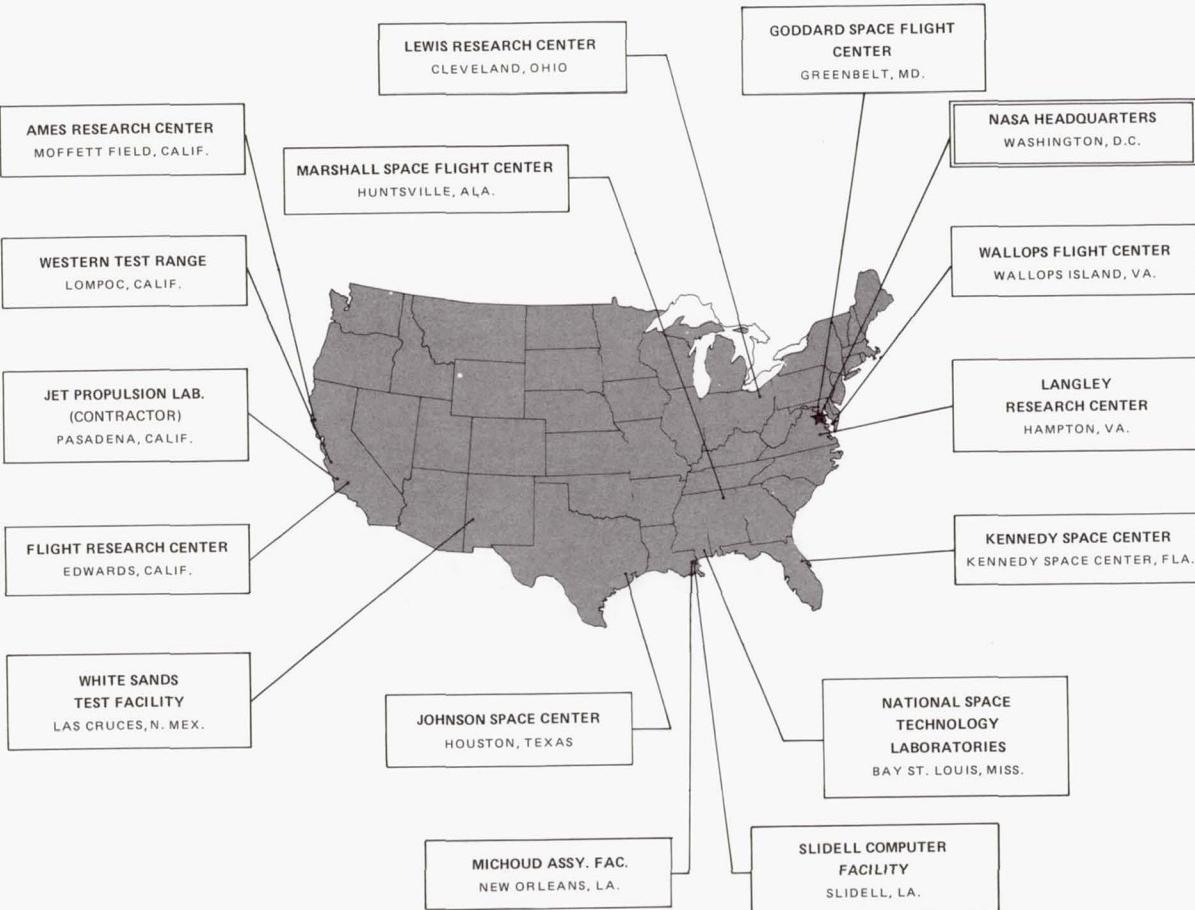


ORGANIZATION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
(November 1963)

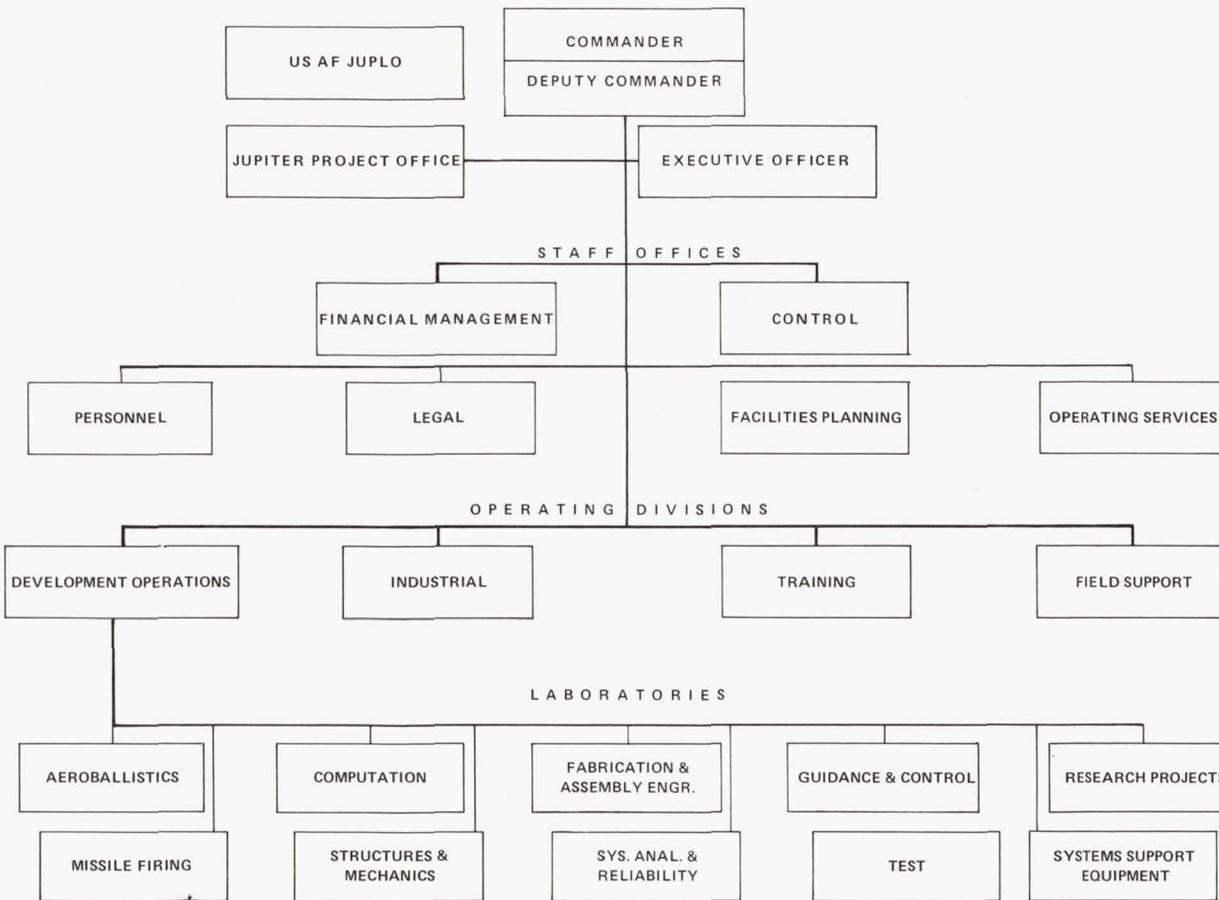


NASA INSTALLATIONS

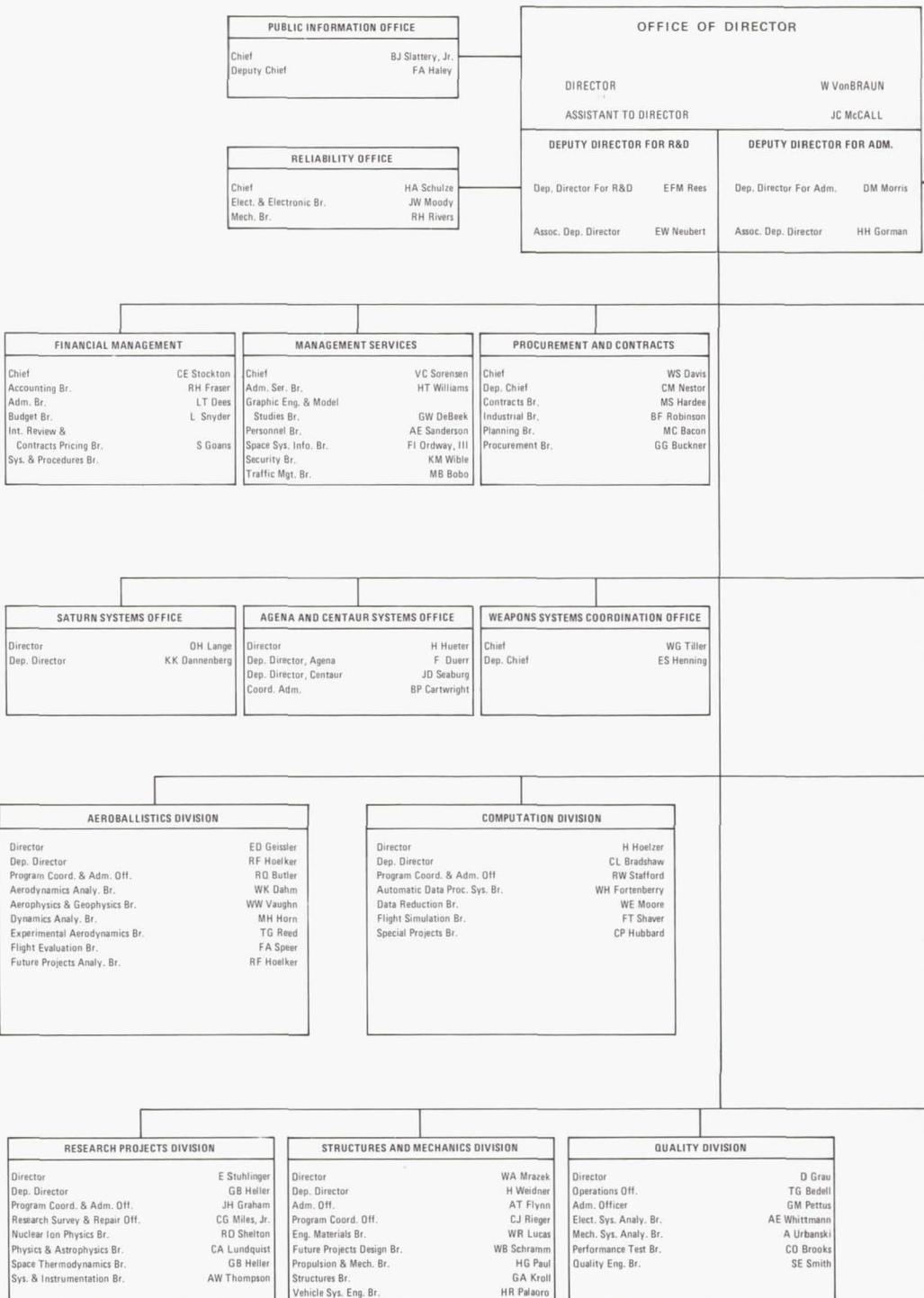


ARMY BALLISTIC MISSILE AGENCY
REDSTONE ARSENAL, ALABAMA

1 JAN 60



APPENDIX G



ORGANIZATION

GEORGE C. MARSHALL SPACE FLIGHT CENTER (November 1960)

LEGAL OFFICE			
Chief Counsel	WE Giulian	Patent Counsel	JH Warden

TECHNICAL SERVICES		OPERATIONS ANALYSIS		NASA RESIDENT AUDITORS	
Chief Eng. Br. Maintenance Br. Operations Br. Photo Br. Program Br. Tech. Materials Br.	DH Newby HC Aden DE Foxworthy HF McMillan SH Hobbs JR Lada WE Beck	CW Huth HA Sleyden PW McClung	Supervisory Auditor	GW Noel	

FUTURE PROJECTS OFFICE		TECHNICAL PROGRAM COORDINATION OFF	
Director Dep. Director	HH Koelle FL Williams	GN Constan TH Smith TU Hardeman WG Crompton	

FABRICATION AND ASSEMBLY ENGINEERING DIVISION		GUIDANCE AND CONTROL DIVISION	
Director Dep. Director Adm. Off. Tech. Liaison Off. Tech. Program Coord. Off. Assembly Eng. Br. Elect-Mech. Eng. Br. Fab. Eng. Br. Methods R&D Br. Plant Eng. & Operations Br.	HH Maus WR Kuers DT Walters J Trott S Heim ME Nowak R Paetz OK Eisenhardt WA Wilson WR Potter	Director Dep. Director Adm. Off. Program Coord. Off. Advanced Studies Br. Applied Research Br. Elect. Sys. Integration Br. Elect-Mech. Eng. Br. Flight Dynamics Br. Gyro. & Stabilizer Br. Instrumentation Dev. Br. Navigation Br. Pilot Manufacturing Dev. Br.	W Haesuermann H Kroeger ML Jensen GF Daussman FE Digesu JC Taylor HJO Fichtner J Boehm HH Hosentien CH Mandel O Hoberg FB Moore W Angele

TEST DIVISION		LAUNCH OPERATIONS DIRECTORATE	
Director Dep. Director Adm. Off. Program Coord. Off. Component Test Facility Br. Measuring Con. & Instrumentation Br. Missile Test Facility Br. Test Facilities Design & Ser. Br.	KL Heimburg BR Tessman WH Dodd TE Edwards BR Tessman WH Sieber DH Driscoll F Kramer	Director Dep. Director Adm. Off. MSFC Liaison Off. Operations Off.	KH Debus HF Grune JB Cobb EG House CC Parker

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Appendix H—MSFC Personnel During Apollo-Saturn

Marshall Space Flight Center
Permanent Civil Service and Contractor Manpower Distribution by Location

	7/15/60	FY-61	FY-62	FY-63	FY-64	FY-65	FY-66	FY-67	FY-68	FY-69	FY-70	FY-71	FY-72
<i>Perm. Civil Service</i>													
Huntsville Area	4824	5688	6469	6394	6749	6705	6594	6495	5918	5671	5578	5454	5098
Outside Huntsville	—	—	64	427	572	622	683	682	522	478	416	306	279
Subtotal	4824	5688	6533	6821	7321	7327	7277	7177	6440	6149	5994	5760	5377
<i>Support/FOC Contractor</i>													
Huntsville Area	1019	2440	3588	5808	6313	5895	5316	5087	4671	3213	2993	3048	3116
Outside Huntsville ^a	—	—	360	720	949	1741	2842	2559	2170	1790	1662	1213	1161
Subtotal	1019	2440	3948	6528	7262	7636	8158	7646	6841	5003	4655	4261	4277
<i>Major Prime Contractor</i>													
Huntsville Area ^b	—	1000 ^c	2705 ^c	4410 ^c	6115 ^c	6818	8116	6517	4755	3165	2393	2042	2122
Outside Huntsville	—	4100	8095	19690	23885	30082	31284	25183	18245	14952	10403	7416	6996
Subtotal	—	5100	10800	24100	30000	36900	39400	31700	23000	18117	12796	9458	9118
<i>Total Manpower</i>													
Huntsville Area	5843	9128	12762	16612	19177	19418	20026	18099	15344	12049	10964	10544	10336
Outside Huntsville	—	4100	8519	20837	25406	32445	34809	28424	20937	17220	12481	8935	8436
Grand Total	5843	13228	21281	37449	44583	51863	54835	46523	36281	29269	23445	19479	18772

^aEnd of Period Headcount except Michoud & MTF

^bFrom PM Qty Rpt

^cEstimated – Data not available.

MSFC Manpower Status Summary as of 30 April 1965

Organization	Civil Service						By Location		
	Vouchered Ceiling	Permanent Personnel			Nonpermanent Personnel			HIC ^b Clinton etc.	Outside Huntsville Area
		On-Board Permanent	On-Board Co-ops	C&E	700-Hr On-Bd.	Summer On-Bd.	Committed Permanent		
Director & Deputies	28	28						28	
Assistant Directors	2	2						2	
Executive Staff	95	83			1		2	84	
Chief Counsel	23	20						20	
Labor Relations Office	5	5						5	
Public Affairs Office	30	30						30	
NASA Audit Office	20	19							12
Facilities & Design Office	108	104	3		2		1	107	2
Financial Management Office	197	188	3		3		1	194	
Management Services Office	210	203			6			176	33
Personnel Office	99	97		1	14			27	85
Purchasing Office	224	222	6		31		1	115	144
Technical Services Office	582	579	2		1			581	1
Unallocated									
Subtotal	1623	1580	14	1	58	0	5	1369	275
									9
Director, R&D Operations	7	7						7	
Future Projects Office	33	31		1				32	
Resources Management Office	50	44						44	

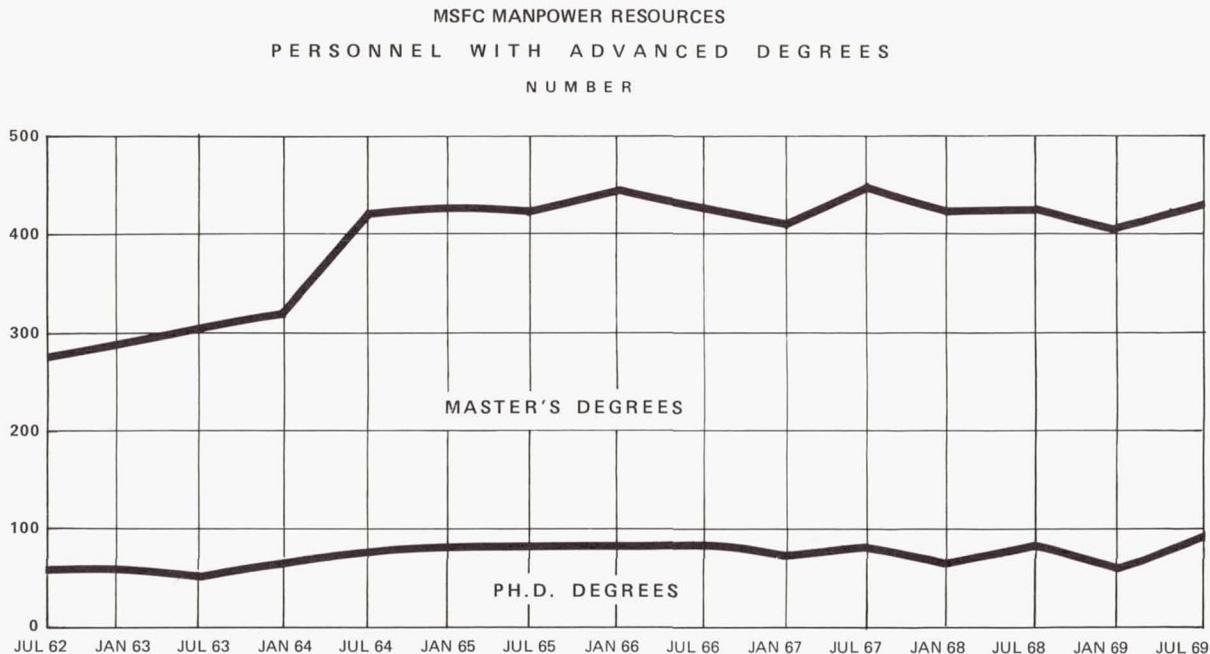
MSFC Manpower Status Summary as of 30 April 1965 — Continued

Organization	Civil Service						By Location		
	Vouchered Ceiling	Permanent Personnel			Nonpermanent Personnel			HIC ^b Clinton etc.	Outside Huntsville Area
		On-Board Permanent	On-Board Co-ops	C&E	700-Hr On-Bd.	Summer On-Bd.	Committed Permanent		
Systems Office	40	35			1			33	3
Aero-Astrodynamics Lab	360	357	27	11	1		1	384	1
Astrionics Lab	944	948	32	2				936	44
Computation Lab	177	174	6	1			1	180	1
Manufacturing Engr Lab	832	832	1		2		2	803	22
Propulsion & Vehicle Engr Lab	817	828	30	7				748	112
Quality & Reliability									
Assurance Lab	629	627	12					535	5
Research Projects Lab	99	87	5		1		6	89	4
Test Lab	741	753	19	1				773	
Unallocated	21								
Subtotal	4750	4723	132	23	5	0	10	4564	184
Director, Independent Operations	18	13						11	2
Saturn IB Centaur Office	8								
Contracts Office	148	145			12		3	127	30
Facilities Project Office	46	44					1	33	11
Project Logistics Office	15	14					1	14	
Resources Management Office	31	30			2		1	32	

MFSC PERSONNEL DURING APOLLO-SAIURN

^aRedstone Arsenal

^bHuntsville Industrial Center and Clinton St. facility



ADVANCED DEGREES—PERCENTAGE OF TOTAL EMPLOYEES

DEGREES	JUL 62	JAN 63	JUL 63	JAN 64	JUL 64	JAN 65	JUL 65	JAN 66	JUL 66	JAN 67	JUL 67	JAN 68	JUL 68	JAN 69	JUL 69
PH.D.	0.8%	0.8%	0.7%	0.9%	1.0%	1.0%	1.0%	1.0%	1.0%	0.9%	1.1%	1.0%	1.2%	1.1%	1.3%
MASTER'S	3.2%	3.2%	3.4%	3.5%	4.5%	4.6%	4.5%	4.8%	4.7%	4.5%	5.0%	5.0%	5.3%	5.2%	5.5%
TOTAL	4.0%	4.0%	4.1%	4.4%	5.5%	5.6%	5.5%	5.8%	5.7%	5.4%	6.1%	6.0%	6.5%	6.3%	6.8%

MARSHALL SPACE FLIGHT CENTER
PERMANENT CIVIL SERVICE AND CONTRACTOR MANPOWER DISTRIBUTION BY LOCATION

	7/15/60	FY-61	FY-62	FY-63	FY-64	FY-65	FY-66	FY-67	FY-68	FY-69	FY-70	FY-71	FY-72
<u>Perm. Civil Service</u>													
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<u>Total Manpower</u>													
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Grand Total	5843	13228	21281	37449	44583	51863	54835	46523	36281	29269	23445	19479	18772

a. End of Period Headcount except Michoud & MTF

b. From PM Qty Rpt

c. Estimated — Data not available

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Notes

CHAPTER 1

1. The name of the locale, Cape Canaveral, was officially changed on 28 Nov. 1963 to honor the late President John F. Kennedy, and the NASA facility was henceforth called John F. Kennedy Space Center (KSC).
2. The official NASA history of Kennedy Space Center and the launch facilities and concepts is by Charles D. Benson and William B. Faherty, *Moonport: A History of Apollo Launch Facilities and Operations*, NASA SP-4204 (Washington, 1978). Material for this section was compiled from the following sources: KSC, *The Kennedy Space Center Story* (Kennedy Space Center, Fla., 1969); NASA, *Astronautics and Aeronautics, 1969: Chronology on Science, Technology, and Policy*, NASA SP-4014 (Washington, 1970); MSFC, "Chronology of MSFC—1969" (draft copy), (1972); NASA, *Saturn V News Reference* (1968); MSFC, *Saturn V Flight Manual*, SA-506 (1969).
3. MSFC, *Saturn V Flight Manual*, SA-506, *passim*; MSFC, *Chronology of MSFC—1969*, *passim*; NASA, *Saturn V News Reference*, *passim*.
4. There are many books covering this period. For a readable and authoritative summary, see the well-illustrated historical survey by Wernher von Braun and Frederick I. Ordway, *History of Rocketry and Space Travel* (New York, 1969), pp. 22–40, which also includes an excellent bibliography. See also Eugene M. Emme, *A History of Space Flight* (New York, 1965), *passim*, which includes a bibliography. For the lifesaving rocket, see Mitchell R. Sharpe, *Development of the Lifesaving Rocket*, Marshall Space Flight Center, Historical Note no. 4, 10 June 1969. The bibliographical study by Katherine Murphy Dickson, *History of Aeronautics and Astronautics: A Preliminary Bibliography*, NASA HHR-29 (Washington, 1968), features annotated entries, and lists many government documents, as well as articles from scholarly journals and periodicals of both European and American origin.
5. For an overview of this era and its leading personalities, see the histories by Loyd S. Swenson, Jr., James M. Grimwood, and Charles C. Alexander, *This New Ocean: A History of Project Mercury*, NASA SP-4201 (Washington, 1966); von Braun and Ordway, *History*; and Emme, *History*. Tsiolkovsky's collected papers are available in translation as NASA Technical Translations F-243, 326, 327 and 328 (1965). For an authorized biography of Goddard see Milton Lehman, *This High Man: The Life of Robert H. Goddard* (New York, 1963); but see also Esther Goddard and G. Edward Pendray, eds., *The Papers of Robert H. Goddard* (New York, 1970), 3 vols. Willy Ley, *Rockets, Missiles, and Men in Space* (New York, 1968) includes considerable historical information. Ley not only knew Oberth and other pioneering figures of the twenties and thirties, he also participated in many experimental projects. Frederick C. Durant, III, and George S. James, eds., *First Steps Toward Space*, Smithsonian Annals of Flight, no. 10 (Washington, 1974), includes a memoir by Oberth, as well as contributions concerning Goddard and the Smithsonian, and essays on rocket research in Europe and the U.S. in the twenties and thirties. Eugene M. Emme,

NOTES TO PAGES 11–19

- ed., *The History of Rocket Technology: Essays on Research Development and Utility* (Detroit, 1964), includes summary essays on U.S. rocket technology in the pre-World War II years.
6. See, for example, von Braun and Ordway, *History*; Emme, *History of Space Travel*; and Swenson, Grimwood, and Alexander, *This New Ocean*. Wartime Russian rocketry is analyzed in Coleman Goldberg, *An Introduction to Russian Rocketry: History, Development, and Prospects*, Off. of the Asst. Chief of Staff, Intelligence. U.S. Army Field Detachment R, 1 June 1959. Copy in JSC files.
 7. Ernst Stuhlinger, et al., eds., *Astronautical Engineering and Science: From Peenemuende to Planetary Space* (New York, 1963), pp. 366–367; von Braun and Ordway, *History*, pp. 63–74.
 8. Dornberger summarizes the V-2 work in Emme, *Rocket Technology*, pp. 29–45, and has published his own memoir, entitled *V-2* (New York, 1954). This book is one of the most authoritative works on the V-2 and Peenemuende generally available, in addition to Dieter K. Huzel, *Peenemuende to Canaveral* (Englewood Cliffs, N.J., 1962); and Krafft A. Ehricke, "The Peenemuende Rocket Center, Part 2," *Rocketscience*, 4 (June 1950):35. See also, Mitchell Sharpe, "Evolution of Rocket Technology: Historical Note, Saturn History Project," Jan. 1974, pp. 15–20 (copy in SHP files); von Braun and Ordway, *History*, 104–117. Practically every aspect of the V-2, from basic research to its early design and testing to its deployment, can be found in a large collection of technical reports from Peenemuende, located in the Redstone Scientific Information Center, U.S. Army Missile Command, Redstone Arsenal, Ala.
 9. Von Braun and Ordway, *History*, pp. 114–117; Dornberger, *V-2*, passim. Plans for rounding up German scientific and technical personnel were in progress by early 1945. During the spring, the idea was known as Operation Overcast. In 1946, the program was renamed Operation Paperclip, the designation which became the most familiar. See Clarence Lasby, *Operation Paperclip* (New York, 1971).
 10. Von Braun and Ordway, *History*, p. 18; Sharpe, "Evolution," pp. 42–48. Between May 1945 and Dec. 1952, the U.S. recruited 642 foreign technicians and specialists under Paperclip. Lasby, *Operation Paperclip*, gives the absorbing details of their utilization by the Air Force, Army, and Navy. Generally, most of the specialists served individually or in very small, close-knit groups. The von Braun team of 132 was by far the largest single group.
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 12. Von Braun and Ordway, *History*, 120 ff.
 13. On the origins of the Redstone Arsenal, see David S. Akens, *Historical Origins of the George C. Marshall Space Flight Center*, MSFC Historical Monograph no. 1 (December, 1960). For accounts of the struggle between the Army and Air Force about the IRBM, see Armacost, *Politics of Weapons Innovation*, and John B. Medaris's memoir, *Countdown for Decision* (New York, 1960). On the role of ABMA, Jupiter, and Polaris, see von Braun and Ordway, *History*, pp. 130–132; Baar and Howard, *Polaris*; Wyndham D. Miles, "The Polaris," in Emme, ed., *Rocket Technology*.
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 17. See, for example, the essay by John P. Hagen, "Viking and Vanguard," cited above; Milton W. Rosen, *Viking Rocket Story* (New York, 1955); Green and Lomask, *Vanguard*. On IGY, Sputnik, and the NASA story, see Emme, *History of Spaceflight*, pp. 120–130; Swenson, Grimwood, and

NOTES TO PAGES 21-32

- Alexander, *This New Ocean*, pp. 18 et seq.; and Robert L. Rosholt, *An Administrative History of NASA, 1958-1963*, NASA SP-4101 (Washington, 1966).
18. For summaries of the era, see, von Braun and Ordway, *History*, pp. 163 passim; Emme, *History of Space Flight*, 153 passim. The official history of the Mercury program is Swenson, Grimwood, and Alexander, *This New Ocean*. For the NASA history of Gemini, see James M. Grimwood and Barton C. Hacker, *On the Shoulders of Titans*, NASA SP-4203 (Washington, 1977). On the Apollo spacecraft and lunar lander, see Courtney G. Brooks, James M. Grimwood, and Loyd S. Swenson, Jr., *Chariots for Apollo: A History of Manned Lunar Spacecraft*, NASA SP-4205 (Washington, 1979).
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 2. H. H. Koelle et al., *Juno V Space Vehicle Development Program, Phase I: Booster Feasibility Demonstration*, ABMA, Redstone Arsenal, Rept. DSP-TM-10-58, 13 Oct. 1958, p. 1. Cited hereafter as *Juno V Feasibility*. Oswald H. Lange, "Development of the Saturn Space Carrier Vehicle," in Stuhlinger et al., *Astronautical Engineering*, pp. 2-23.
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27. Akens, *Saturn Chronology*, p. 5.
28. Milton W. Rosen interview, NASA, 14 Nov. 1969.
29. ARPA, “Saturn Chronology,” pp. 14–15.
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31. Herbert F. York to Eugene Emme, 2 May 1973; ARPA, “Saturn Chronology,” pp. 5–6.
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NOTES TO PAGES 43-55

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47. Abraham Hyatt to Thomas O. Paine, 25 Nov. 1969; Hyatt to Eugene Emme, 21 Mar. 1973; von Braun, "Saturn the Giant," p. 41.
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67. Cited in Emme, "Perspectives," p. 378.
68. House Committee on Science and Astronautics, *1962 NASA Authorization Hearings*, 87 Cong., 1st sess., Mar.-Apr. 1961, pp. 1-5, 31, 374-378.
69. *Public Papers . . . Kennedy*, 1962 (Washington, 1963), pp. 688-674. For additional background, see Courtney Brooks, James Grimwood, and Loyd S. Swenson, Jr., *Chariots for Apollo: A History of Manned Lunar Spacecraft*, NASA SP-4205 (Washington, 1979), Chapter 1. For a thorough review and assessment of this era and Kennedy's historic decision, see the fine study by Logsdon, *The Decision to Go to the Moon*.

NOTES TO PAGES 57-65

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7. "Discussion Notes, Lunar Landing Steering Group," memo, 31 July 1961. Among the dozen attendees, including Rosen, were Seamans, Silverstein, Gilruth, and Eberhard Rees, von Braun's top deputy from MSFC.
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14. Robert R. Gilruth to Staff, "Advanced Vehicle Team," 25 May 1960, JSC files.
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21. John C. Houbolt to Robert C. Seamans, 15 Nov. 1961, JSC files.
22. Milton W. Rosen to D. Brainerd Holmes, "Large Launch Vehicle Program," 6 Nov. 1961, JSC files. For details and membership of these various groups, see Logsdon, "Selecting," and Brooks, Grimwood, and Swenson, *Chariots for Apollo*.
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24. Logsdon, "Selecting," p. 68.
25. Milton Rosen, interview, NASA, 14 Nov. 1969.

26. Quoted in Logsdon, "Selecting," p. 68.
27. A. T. Mattson to Charles J. Donlen, "Report on Activities 16 Apr. to 19 Apr. 1962, Regarding Manned Spacecraft Projects," 20 Apr. 1962, JSC files.
28. D. Brainerd Holmes to von Braun, 4 June 1962, JSC files.
29. Von Braun, "Concluding Remarks by Dr. Wernher von Braun About Mode Selection for the Lunar Landing Program Given to Dr. Joseph F. Shea, Deputy Dir. (Systems) Off. of Manned Space Flight," memo for the record, June 1962, pp. 1-5.
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NOTES TO PAGES 76-91

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44. MSFC, *Saturn I Summary*, TMX 57401, 15 Feb. 1966, unpage; Akens, *Saturn Chronology*, pp. 28–31; Lange, "Development," *Astronautical Engineering*, pp. 15–16.
45. Chrysler Corp., Space Div., "Saturn IB Orientation: Systems Training Manual," no. 851-0, 15 Feb. 1965, pp. 2–3; Akens, *Saturn Chronology*, pp. 39, 42; MSFC, *Saturn IB News Reference*, Sept. 1968, pp. 1.2–1.3; MSFC, Historical Off., *History of MSFC, July 1-December 31, 1962*, MHM-6, May 1963, pp. 169–181.
46. For an explanation of the Saturn IB weight saving program, see H. D. Lowrey, "The Saturn IB Launch Vehicle System," speech to Soc. of Automotive Engineers, Detroit, Mich., 9 Nov. 1964. For overall system description, manufacturing, and operations, see Chrysler, "Saturn IB Orientation"; MSFC, *Saturn IB News Reference*; MSFC, *Saturn IB Launch Vehicle Project Development Plan*, NASA-TM-X-60121, 1 Jan. 1967; MSFC, *Technical Digest*, pp. 76–77, 81–82. For detailed description, and cut-away drawings of major systems and components, see MSFC, *Saturn IB Vehicle Handbook*, vol. 1, "Vehicle Description," vol. 2, "S-IB Stage," CR-81077, 25 July 1966.

CHAPTER 4

1. Michael T. Davis, Robert K. Alleger, Jr., Thomas G. Rogers, and Gordon Rysavy, *The Development of Cryogenic Storage Systems for Space Flight* (Washington, 1970), p. 1.
2. Davis et al., *Cryogenic Storage*, p. 12. For a highly technical review of cryogenic research, see the contribution of John A. Clark, "Cryogenic Heat Transfer," in Thomas F. Irvin, Jr., and James P. Harnett, eds., *Advances in Heat Transfer* (New York, 1968), 5: 325–517. For description of cryogenic production techniques and applications, see the articles "Cryogenics" and "Cryogenic Engineering" in the *McGraw-Hill Encyclopedia of Science and Technology* (New York, 1960), pp. 569–75.
3. There were significant milestones in the development of other missiles and launch vehicles which used either solid propellant motors or other kinds of liquid propellants. The first upper-stage liquid rocket engine, for example, originated in the Vanguard program, using nitric acid and unsymmetrical dimethylhydrazine as propellants.
4. Leland F. Belew, W. H. Patterson, and J. W. Thomas, Jr., "Apollo Vehicle Propulsion Systems," AIAA Paper 65–303, July 1965, pp. 1–2.
5. Edward E. Straub, "The H-1 Engine," *Astronautics*, 7 (Feb. 1962): 39; A. A. McCool and Keith B.

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- Chandler, "Development Trends of Liquid Propellant Engines," in Ernst Stuhlinger et al., eds., *From Peenemuende to Outer Space* (Huntsville, Ala., 1962), pp. 294-96.
6. William J. Brennan, "Milestones in Cryogenic Liquid Propellant Rocket Engines," AIAA Paper 67-978, Oct. 1967, passim.
 7. For an overview of these and related topics, see Brennan, "Milestones," pp. 10-13. For a technical discussion of early thrust chamber designs, consult Heinz H. Koelle, ed., *Handbook of Astronautical Engineering* (New York, 1961), pp. 20.69-20.75. Theories on thrust chambers prevalent in the late sixties are discussed in Dieter K. Huzel and David H. Huang, *Design of Liquid Propellant Rocket Engines*, 2d ed. (Washington, 1971), pp. 81-120. See especially the illustration on p. 113, depicting variations in tube cross sections. Koelle, *Handbook*, pp. 20.90-20.99, includes analysis of turbopump design parameters. For a more extended treatment, see Huzel and Huang, *Design*, pp. 176-261. Gas generators are also described in Koelle, *Handbook*, pp. 20.102-20.105, and in Huzel and Huang, *Design*, pp. 131-36.
- For clarification of many details of propulsion system design and operation covered in Chapters 4 and 5, the author wishes to acknowledge interviews with Leonard Bostwick and Milan Burns, MSFC, 31 July 1975, and with Joseph Attinello, Robert Fontaine, and Paul Fuller, Rocketdyne, 4 Mar. and 10 Mar., 1971.
8. A. J. Burks, "Development of LOX-Hydrogen Engines for the Saturn Apollo Launch Vehicles," MSFC, Engine Program Off., 10 June 1968, p. 1. At the time, Burks was the assistant manager of the office. Although this report applied specifically to LOX-LH₂ systems, his comment on engines as the pacing item applied to propulsion systems in general.
 9. Leonard C. Bostwick, "Development of LOX/RP-1 Engines for Saturn/Apollo Launch Vehicles," AIAA Paper for Propulsion, Joint Specialist Conf., June 1968, p. 1.
 10. Bostwick, "Development of LOX/RP-1 Engines"; Belew, Patterson and Thomas, "Apollo Propulsion Systems."
 11. Akens, *Saturn Chronology*, p. 3; MSFC, *Launch Vehicle Engines: Project Development Plan* (MA 001-A50-2H), 1 July 1965, p. 2.5. The direct antecedents of the H-1 included not only the Thor and Jupiter engine system designs, but also designs from three other engine development programs, known as the MA-3, the X-1 and the S-4.
 12. "Saturn H-1 Engine Design Features and Proposed Changes," ORDAB-DSDE, 21 Sept. 1959, DSDDE memo no. 2017; MSFC, *Launch Vehicle Engines*, pp. 2.1, 2.6; Rocketdyne, "News from Rocketdyne: Data Sheet, H-1 Rocket Engine," 15 July 1968.
 13. Emme, *Aeronautics and Astronautics*, p. 109; Rocketdyne, "News/Data Sheet, H-1"; Straub, "The H-1 Engine," pp. 39, 96. Straub was a Rocketdyne engineer involved with the H-1 engine from its inception. Engine production continued under NASA cognizance after the formal transfer of specified ARPA and ABMA projects on 16 Mar. 1960.
 14. MSFC Saturn Off., *Saturn Monthly Progress Report*, 16 Nov.-12 Dec. 1963, pp. 5-6; MSFC Engine Project Off., *H-1 Engine Project Development Plan*, 1 Dec. 1963, pp. 33-38; MSFC Engine Project Off., *Engine Quarterly Report*, Apr.-June, 1964, p. 21; MSFC, *Michoud Assembly Facility Historical Report*, 1 Jan.-30 June 1965, pp. 5, 23; MSFC Industrial Operations, Engine Program Off., *Quarterly Progress Report: F-1, H-1, J-2 and RL-10 Engines, January-March, 1965*, 15 Mar. 1965, pp. 15-16; Paul Anderson, Contracts Off., MSFC, "Contract NAS8-18741," 30 June 1967.
 15. MSFC, *Launch Vehicle Engines*, p. 9.5; Bostwick and Burns interview; Attinello, Fontaine, and Fuller interviews.
 16. MSFC, *Launch Vehicle Engines*, pp. 2.6, 3.23; Rocketdyne, *H-1 Rocket Engine Technical Manual R-3620-1: Engine Data*, 1968, pp. 1.1, 1.8, 1.28; Belew, Patterson, and Thomas, "Apollo Vehicle Propulsion Systems," p. 2; MSFC, *Saturn IB News Reference*, Sept. 1968, pp. 4.1-4.2, 4.6; Straub, "H-1 Engine," pp. 39, 36.
 17. Belew, Patterson, and Thomas, "Apollo Propulsion Systems," p. 3; Bostwick, "Development of LOX/RP-1 Engines," pp. 3-4.
 18. Charles E. Cataldo, *H-1 Engine LOX Dome Failure*, NASA TM X-53220, July 1964, pp. 1-4; KSC to Apollo Program Dir., Hq., teletype, "SA-7 Launch Schedule," 17 July 1964; Apollo Spacecraft Program Off., Hq. to KSC, teletype, "SA-7 Launch Schedule," 22 July 1964; Belew, Patterson, and Thomas, "Apollo Propulsion Systems," p. 3; Bostwick, "Development of LOX/RP-1 Engines," p. 4.
 19. Belew, Patterson, and Thomas, "Apollo Propulsion Systems," p. 3; Bostwick, "Development of LOX/RP-1 Engines," p. 5.

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20. Arthur W. Thomson, "Meeting Held December 1, 1966 to Review Problems with the H-1 Engine on S-IB-7 and S-IB-8," 1 Dec. 1966 memo for record.
21. Ibid; Bostwick, "Development of LOX/RP-1 Engines," pp. 5–6.
22. Belew, Patterson, and Thomas, "Apollo Propulsion Systems," p. 3; Bostwick, "Development of LOX/RP-1 Engines," pp. 6–7.
23. Akens, *Saturn Chronology*, p. 4; David E. Aldrich, "The F-1 Engine," *Astronautics*, 7 (Feb. 1962): 40; David E. Aldrich and Dominick J. Sanchini, "F-1 Engine Development," *Astronautics*, 7 (Mar. 1961):24. Aldrich at the time was Rocketdyne's manager and chief engineer on the F-1 engine project; Sanchini was the assistant engineer.
24. Belew, Patterson, and Thomas, "Apollo Propulsion Systems," p. 5; MSFC, *Launch Vehicle Engines*, p. 2.3; Emme, *Aeronautics and Astronautics*, p. 77.
25. Belew, Patterson, and Thomas, "Apollo Propulsion Systems," p. 4; Bostwick and Burns interview; MSFC, *Launch Vehicle Engines*, p. 2.3.
26. Aldrich and Sanchini, "F-1 Development," p. 25; MSFC, *Launch Vehicle Engines*, p. 2.3; Brennan, "Milestones," p. 9.
27. Franklin L. Thistle, "Rocketdyne: The First 25 Years," North American Rockwell Corp., 1970, pp. 22, 25, 28; Aldrich, "F-1," p. 96; Belew, Patterson, and Thomas, "Apollo Propulsion Systems," p. 5; Rocketdyne, "Data Sheet: F-1 Rocket Engine," 12 Dec. 1967; Aldrich and Sanchini, "F-1 Development," p. 47; MSFC, *Launch Vehicle Engines*, pp. 9.4–5.
28. Joseph P. McNamara interview, North American Rockwell, 5 Mar. 1971; Brennan, "Milestones," p. 8; MSFC, *Launch Vehicle Engines*, p. 2.4.
29. Aldrich, "F-1," p. 40; Belew, Patterson, and Thomas, "Apollo Propulsion Systems," pp. 4–5; Brennan, "Milestones," p. 8; MSFC, *Launch Vehicle Engines*, p. 2.4.
30. MSFC, *Saturn V News Reference*, Dec. 1968, 3.1 and following.
31. Aldrich and Sanchini, "F-1 Development," pp. 46–47; Aldrich, "F-1," p. 69; MSFC, *Saturn V News Reference*, 3.1–2; Aldrich and Sanchini, "Design and Development of a 1 500 000-Pound-Thrust Space Booster Engine," Rocketdyne Report, July 1963, pp. 2–3.
32. Bostwick, "Development of LOX/RP-1 Engines," p. 9.
33. Hugh Dryden to Hugh Odishaw, 6 Mar. 1961.
34. Bostwick, "Development," p. 9; Akens, *Saturn Chronology*, pp. 49, 88; MSFC Historical Off., *History of the George C. Marshall Space Flight Center From July 1 Through December 31, 1962*, MHM-6 (1963), p. 131; von Braun to Seamans, draft of memo, 1962. Although the memo itself is undated, internal evidence indicates it was prepared late in Nov. 1962, following a meeting of the Off. of Manned Space Flight on 17 Nov. Copy in the personal files of Jerry Thomson, MSFC, examined by the author on 27 July 1972. Cited hereafter as MSFC, Thomson files.
35. Jerry Thomson to multiple addressees, "Activities CSAHC from Inception to September 1, 1962," 21 Sept. 1962; Jerry Thomson to multiple addressees, "Minutes 2nd Meeting CSAHC 2–3 October at Rocketdyne," 17 Oct. 1962. MSFC, Thomson files.
36. Von Braun to Seamans, draft of memo, 1962; Jerry Thomson to multiple addressees, "Minutes . . . Meeting on F-1 Engine Combustion Instability . . . December 4, 1962." MSFC, Thomson files.
37. Jerry Thomson to Rocketdyne, letter draft, Dec. 1962; S.F. Morea, "Presentation to Mr. D. Brainerd Holmes on F-1 Combustion Stability Effort—January 31, 1963," memo for record, 18 Feb. 1963; A. O. Tischler, "Meeting on F-1 Combustion Stability Effort—January 31, 1963," memo for record, 18 Feb. 1963; A. O. Tischler, "Meeting on F-1 Combustion Instability at NASA HQ, 31 January 1963," memo for record (all in MSFC, Thomson files); Holmes to Seamans, 4 Feb. 1963, copy in SHP files.
38. Holmes to von Braun, 25 Mar. 1963. MSFC, Thomson files.
39. Bostwick, "Development," p. 9; Akens, *Saturn Chronology*, pp. 49, 88.
40. Crocco to von Braun, 13 May 1963; Jerry Thomson, memo for record, autumn 1963; Hugh Dryden to von Braun, 4 Feb. 1964. MSFC, Thomson files.
41. Jerry Thomson, "Minutes of 6th Combustion Ad Hoc Committee . . . 4–5 December 1963," memo for record; Crocco and Harrje to Thomson, 29 July 1964; Crocco to P. D. Castenholz, 16 Aug. 1964. MSFC, Thomson files.

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42. Brennan, "Milestones," p. 9; Bostwick, "Development," p. 9; McNamara interview; Robert Fontaine interview, 4 Mar. 1971, and 10 Mar. 1971; Bostwick and Burns interview, 31 July 1975.
43. Brennan, "Milestones," p. 9; contractor briefing session, Rocketdyne, 4 Mar. and 10 Mar. 1971.
44. NASA/MSFC Resident Off., Rocket Test Site, Edwards, Calif. to S. F. Morea, MSFC, "Weekly Report Ending 15 April 1965," teletype; NASA/MSFC F-1 Project Off., Rocketdyne/Canoga Park, Calif., to S. F. Morea, MSFC, "Weekly Report Ending 15 January 1965," teletype.
45. NASA/MSFC F-1 Project Off., Rocketdyne/Canoga Park, Calif. to S. F. Morea, MSFC, "Weekly Report Ending 25 June 1965," teletype; Leland Belew to General S. C. Phillips, "Apollo Flash Report," telegram, 1 July 1965 and 9 July 1965; NASA/MSFC F-1 Project Off., Rocketdyne/Canoga Park, Calif., to S. F. Morea, MSFC, "Weekly Report Ending 20 August 1965," teletype; Bostwick, "Development," p. 10.
46. Aldrich, "F-1," p. 69.
47. MSFC, *Saturn V News Reference*, pp. 3.4–5.
48. Bostwick, "Development," pp. 9–10; McNamara interview; contractor briefing sessions, Rocketdyne, 4 Mar. and 10 Mar. 1971.
49. Belew et al., "Apollo Propulsion Systems," pp. 5–6; Aldrich, "F-1" p. 40; Aldrich and Sanchini, "Design and Development," pp. 8–10; David E. Aldrich, "Saturn V Booster—The F-1 Engine," Rocketdyne Report, Mar. 1965, p. 18.
50. Aldrich, "Saturn V Booster," p. 4; Aldrich and Sanchini, "Design and Development," p. 2; Belew et al., "Apollo Propulsion Systems," p. 6; MSFC, *Saturn V News Reference*, pp. 3.1–2.
51. Aldrich, "Saturn V Booster," p. 13; Francis X. de Carlo, "Furnace Brazing," Rocketdyne Report, undated, pp. 1, 5, 7, 10.
52. De Carlo, "Furnace Brazing," pp. 11, 14, 17, 32, 33; Ernst G. Huschke, Jr., "Furnace Brazing of Liquid Rocket Engines," Rocketdyne Report, 1963, *passim*.
53. Aldrich, "Saturn V Booster," pp. 4, 18; Aldrich and Sanchini, "Design and Development," pp. 5, 6; Bostwick, "Development"; MSFC, *Saturn V News Reference*, pp. 3.2–3, 3.6–7, 3.10.
54. Aldrich and Sanchini, "F-1 Development"; MSFC, "Launch Vehicle Engines," pp. 9.4–5.
55. Akens, *Saturn Chronology*, *passim*; Thistle, "25 Years," pp. 35, 40, 44; Rocketdyne, "Data Sheet: F-1," p. 1.
56. *Marshall Star*, "Engine Storage Lifetime Extended by Tests Here," 2 June 1971; *Marshall Star*, "F-1 Engine Is Static Fired After Storage," 12 July 1972. Apparently, selected J-2 engines were also fired about the same time.
57. Straub, "H-1 Engine," p. 39.

CHAPTER 5

1. Rocketdyne, "Propulsion: The Key to Moon Travel," 1964. For a richly detailed history of LH₂ development by an engineer who participated in many of the key research programs and knew virtually all the participants, see John L. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*, SP-4404, (Washington, 1978).
2. There are numerous books on dirigible technology and the use of hydrogen gas. See, for example, Douglas H. Robinson, *Giants in the Sky* (Seattle, WA, 1973). A translation of Tsiolkovsky's 1903 treatise, discussing liquid hydrogen fuels, is included in NASA, *Collected Works of K. E. Tsiolkovsky*, vol. 2, NASA TTF-237, pp. 72–117. For a brief discussion of LH₂ research, see John D. Clark, *Ignition: An Informal History of Liquid Rocket Propellants* (New Brunswick, N. J., 1972), pp. 103–114.
3. George H. Osburn, Robert Gordon, and Herman L. Coplen, "Liquid Hydrogen Rocket Engine Development, 1944–1950" (a paper presented at the 21st International Astronautical Congress, Constance, West Germany, 1970), p. 1; R. Cargill Hall, "Early U.S. Satellite Proposals" in Emme, *The History of Rocket Technology*, p. 75 *passim*; Richard S. Lewis, *Appointment on the Moon* (New York, 1968), p. 28. The story of von Kármán's achievements is recounted in his autobiography, *The Wind and Beyond* (Boston, 1967).

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4. General Dynamics/Astronautics, *A Primer of the National Aeronautics and Space Administration's Centaur* (San Diego, 1964), p. 3. Osburn, Gordon, and Coplen, "Liquid Hydrogen Development," pp. 3–4, 9; Sloop, *Liquid Hydrogen*, pp. 64 ff.
5. Osburn, Gordon, and Coplen, "Liquid Hydrogen Development," pp. 3, 9–10, 12. The Osburn paper also includes detailed explanations of the production and handling of liquid hydrogen in the pioneer facility.
6. The quotation is from Lewis, *Appointment*, p. 34. Sources for this portion of the narrative include Lewis, *Appointment*, pp. 29–34; and Hall, "Early Proposals." See also Constance M. Green and Milton Lomask, *Vanguard: A History* (Washington, 1971), pp. 1–24.
7. John Sloop, "NACA High Energy Rocket Propellant Research in the Fifties" (a paper presented at the AIAA 8th Annual Meeting, Washington, D.C., 1971), unpagged. See also, Sloop, *Liquid Hydrogen*, pp. 71 ff., for early Lewis work and for Krafft Ehricke's work at GD/A.
8. Sloop, "NACA Rocket Research," John L. Sloop interview, NASA Hq., 2 Dec. 1971.
9. Sloop, "NACA Rocket Research"; Sloop, *Liquid Hydrogen*, pp. 187 ff.
10. General Dynamics/Astronautics, *Centaur Primer: An Introduction to Hydrogen-Powered Space Flight* (San Diego, 1962), pp. x–xi.
11. General Dynamics, *Centaur Primer*, p. 1. For an account of the Atlas program, consult J. L. Chapman, *Atlas: The Story of a Missile* (New York, 1960).
12. General Dynamics, *Centaur Primer*, pp. 12–13. For early LH₂ work in jets, see Sloop, *Liquid Hydrogen*, pp. 113 ff. For Pratt and Whitney's effort, see *ibid.*, pp. 149 ff.
13. Lewis, *Appointment*, pp. 261–62; General Dynamics, *Centaur Primer*, p. 1; General Dynamics, *NASA Centaur*, p. 3; MSFC, "Launch Vehicle Engines: Project Development Plan," 1 July 1965, pp. 9, 11.
14. Oswald H. Lange, "Development of the Saturn Space Carrier Vehicle," in Stuhlinger et al., *Astronautical Engineering and Science* (New York, 1963), pp. 4–5.
15. General Dynamics, *Centaur Primer*, pp. 1–2; Lewis, *Appointment*, pp. 261–62. Col. Donald Heaton to Hyatt, NASA Hq., "RL-10 Engine Management Arrangements," 14 Jan. 1960.
16. David S. Akens, *Saturn Illustrated Chronology: Saturn's First Eleven Years, April 1957 through April 1968*, MSFC, MHR-5, 1971, pp. 10, 14, 16–17, 30, 39.
17. Emme, *Aeronautics and Astronautics*, pp. 93, 103; Sloop, *Liquid Hydrogen*.
18. Douglas Aircraft Corp., "Saturn Data Summary Handbook," Douglas Rept. no. N66-28064, 1 Oct. 1965, pp. 10–11; Frank Ginsti, "Engineering's Prized New Ally," *United Aircraft Quarterly Bee-Hive*, 37 (Jan. 1962): 34–36.
19. Jerry Thomson interview, MSFC, 21 July 1972; David L. Christensen interview, Univ. of Alabama, Huntsville, 25 Mar. 1971. Thomson was a key engineer in the engine program at MSFC. Christensen, also an engineer, had worked at ABMA, then as a technical liaison for the Pall Corp.
20. General Dynamics, *Centaur Primer*, pp. 11–12; Leland F. Belew, Floyd Drummond, and Rodney D. Stewart, "Recent NASA Experience with Hydrogen Engines," AIAA Paper 64–270, 1964, pp. 2–3. Leland F. Belew, W. H. Patterson, and J. W. Thomas, Jr., "Apollo Vehicle Propulsion Systems," AIAA Paper 65–303, July 1965, p. 7.
21. William J. Brennan, "Milestones in Cryogenic Liquid Propellant Rocket Engines"; Belew, Patterson, and Thomas, "Apollo Vehicle," p. 9; Pratt & Whitney, "News Release," 1965. For additional details, see, A. A. McCool and G. H. McKay, Jr., "Propulsion Development Problems Associated with Large Liquid Rockets," MSFC, TM X-53075, 12 Aug. 1963, pp. 16–19.
22. Belew, Patterson, and Thomas, "Apollo Vehicle," p. 7, *passim*; Belew, Drummond, and Stewart, "Recent NASA Experience," pp. 1–2.
23. Rocketdyne, "J-2 Rocket Engine: Background Information, press release; Saturn Vehicle Team," Report to the Administrator, NASA, on Saturn Development Plan," 15 Dec. 1959.
24. Floyd M. Drummond interview, MSFC, 1 Sept. 1971; Rocketdyne, "J-2 Rocket Engine," pp. 2–3; W. R. Studhalter, "The J-2 Liquid Hydrogen Rocket Engine," Society of Automotive Engineers, SAE Paper no. 687 B, 1963, p. 20.
25. Rocketdyne, "J-2 Rocket Engine," p. 3.
26. Contractor facility tour and briefing, 4 Mar. 1971; Jack Monaghan interview, Rocketdyne, 4 Mar. 1971.

NOTES TO PAGES 143–158

27. Rocketdyne, "J-2 Rocket Engine," pp. 3–5; Belew, Patterson, and Thomas, "Apollo Vehicle," p. 10; MSFC, Saturn Systems Off., *Saturn Monthly Progress Report*, 12 Apr.–12 May 1962, pp. 12–13; ibid., 14 May–12 June 1962, p. 11; MSFC, Saturn Off., *Saturn MPR*, 15 Sept.–15 Oct. 1962, pp. 5–6.
28. Akens, *Saturn Chronology*, pp. 39, 50; NASA News Release, July 11, 1962.
29. Rocketdyne, "J-2 Rocket Engine," pp. 4–5.
30. Ibid.; Paul Fuller, "Liquid Hydrogen Technology, J-2 Engine" (a paper presented to a meeting of the AIAA, July 1965), pp. 4–5.
31. Thomson interview; Christensen interview; Drummond interview; Robert Pease interview, MSFC, 3 Sept. 1971; Richard N. Rodgers interview, MSFC, 24 Aug. 1971.
32. Rocketdyne, "Existing Technology," p. 2; Rocketdyne, "J-2 Engine," p. 4. MSFC, *Saturn V News Reference*, pp. 6.1–6.2; Fuller, "Liquid Hydrogen Technology," p. 2.
33. Studhalter, "J-2 Rocket Engine," pp. 5–8; MSFC, *Saturn V News Reference*, p. 6.1.
34. Studhalter, "J-2 Rocket Engine," p. 3; Brennan, "Milestones," p. 6; Rocketdyne, "Existing Technology Utilized in J-2 Engine System Design," 10 Mar. 1971, p. 5.
35. Studhalter, "J-2 Rocket Engine," pp. 3, 5. Tank pressures in the vehicle were kept low to save the weight of heavier test tank construction. Each pump had a very efficient inducer stage to operate at low pressures. The NPSH for LH₂ at 4 psia was 40 meters, and NPSH for LOX at 12.5 psia was 7.6 meters.
36. Fuller, "Liquid Hydrogen Technology," pp. 3–4; Rocketdyne, "J-2 Engine . . . Change Points," 9 March 1971, p. 1; MSFC, *Saturn V News Reference*, pp. 6.6–6.7.
37. Brennan, "Milestones," p. 8; Studhalter, "J-2 Rocket Engine," p. 9; Rocketdyne, "Existing Technology," pp. 1–2; MSFC, *Saturn V News Reference*, pp. 6.2–6.4.
38. Belew, Drummond, and Stewart, "Recent NASA Experience," pp. 3–4; Studhalter, "J-2 Rocket Engine," pp. 9, 13; Brennan, "Milestones," p. 8; Rocketdyne, "Existing Technology," p. 4; Fuller, "Liquid Hydrogen Technology," p. 2; John L. Sloop to Monte Wright, NASA, 8 July 1976.
39. Rocketdyne, "J-2 Rocket Engine," pp. 5–6; Akens, *Saturn Chronology*, pp. 71, 78–79, 98; Fuller, "Liquid Hydrogen Technology," p. 5; Belew, Patterson, and Thomas, "Apollo Vehicle," p. 12.
40. DAC, *Saturn S-JVB Monthly TRP*, July 1965, p. 48; MSFC Engine Program Off., *Semiannual Progress Report*, July-Dec., 1965, pp. 21–23; MSFC files. MSFC press releases, nos. 66–4 and 66–8, 7 Jan. 1966; Rocketdyne, "J-2 Engine," p. 6; Akens, *Saturn Chronology*, pp. 115–16, 130–31; MSFC Test Lab, *Historical Report*, Jan.–Dec. 1965, pp. 7–8. For details of flight missions, see Chapters 11 and 12.
41. Akens, *Saturn Chronology*, pp. 110, 145, 175; MSFC Press Release no. 67–39, 28 Feb. 1967; MSFC, Saturn V Program Off., *Saturn V Semiannual Progress Report*, Jan.–June 1967, pp. 68–72; MSFC files; *Saturn V Semiannual Progress Report*, July–Dec. 1967, pp. 76–79; MSFC files.
42. Studhalter, "J-2 Rocket Engine," pp. 5, 7; Belew, Drummond, and Stewart, "Recent NASA Experience," p. 3.
43. Studhalter, "J-2 Rocket Engine," p. 17.
44. Drummond interview; Pease interview; Rodgers interview.
45. Belew, Patterson, and Thomas, "Apollo Vehicle," p. 1; Pease interview.
46. Rocketdyne, "J-2 Rocket Engine," p. 4; Studhalter, "J-2 Rocket Engine," pp. 20, 26. The composition of Invar included Fe 63%; Ni 36%; other 1%.

CHAPTER 6

1. William A. Mrazek, "Launch Vehicle Systems," in NASA, "Science and Technology Committee for Manned Space Flight," (MSC, Houston, Tex., 29 June 1964), I: 1–2, cited hereafter as STAC Conference; Akens, *Saturn Illustrated Chronology*, p. 50.
2. Abraham Hyatt to the Associate Administrator, "Meeting with Director, Development Operations Division, ABMA, Huntsville," 11 Jan. 1960; von Braun to Maj. Gen. Don F. Ostrander (USAF), NASA, 8 Jan. 1960; Abraham Hyatt to von Braun, 18 Jan. 1960.

NOTES TO PAGES 158-165

3. Maj. Gen. Don Ostrander, NASA, to von Braun, 26 Jan. 1960; minutes, "Saturn Orientation Conference," 26-27 Jan. 1960. The latter is a verbatim copy, taped during the two-day session.
4. Abraham Hyatt to O. H. Lange, 22 June 1960.
5. T. Keith Glennan, "Administrator's Statement on the Selection of a Contractor for the Saturn S-IV Stage," memo, 28 Apr. 1960; Akens, *Saturn Chronology*, pp. 8, 10, 13.
6. Glennan memo, "Administrator's Statement." By the fall of 1960, Convair won the S-V contract, but the future of this third stage became marginal. In Jan. 1961, von Braun recommended a change in the C-1, from three to two stages, and NASA management concurred. The development of the S-V subsequently was canceled.
7. Controller General of the U.S. to Overton Brooks, Chmn., Comm. on Science and Astronautics, 22 June 1960; Committee on Science and Astronautics news release, 18 July 1960. Evidently, there were questions about the significance of Chrysler's proposal to build its own plant near Cape Canaveral. This would have entailed government funds and equipment, the GAO noted. In any case, Chrysler's technical proposal received very low ratings. See, for example, Milton W. Rosen, "Technical Evaluation of Saturn S-IV Proposal; Comments On," memo, 8 June 1950. For additional comment on NASA procurement policies, see Vernon van Dyke, *Pride and Power* (Urbana: University of Illinois Press, 1964), pp. 214-16.
8. John Mazur, "Chronological Summary of Negotiations of Saturn . . . Vehicle Stage S-IV . . .," memo, May 1960; von Braun to Ostrander, 18 May 1960; von Braun to Ostrander, "Agreements and Design Assumptions of First Saturn S-IV Coordination Conference," with attachments, 15 June 1960.
9. Akens, *Saturn Chronology*, pp. 8, 10, 13.
10. Oswald H. Lange, "Development of the Saturn Space Carrier Vehicle," in Stuhlinger, et al., *Astronautical Engineering*, pp. 8, 18; Akens, *Saturn Chronology*, pp. 14, 16-17, 20, 31, 35.
11. The S-I first-stage booster for Saturn I made 10 launches, including 5 with a live S-IV stage. The S-IVB third stage made 5 launches with the Saturn IB, and 6 more on the Saturn V through the first lunar landing (AS-506). By the time of the final Apollo-Saturn mission (AS-512), the S-IVB notched 6 more launches for a total of 17 flights. The first two stages of the Saturn V, the S-IC and the S-II, had an even dozen launches on Apollo missions. The S-IC/S-II combination also launched the Skylab orbital workshop. The last 4 Saturn IB/S-IVB launches involved three Skylab crews and the ASTP crew, for a grand total of 21 S-IVB flights.
12. MSFC, "S-IVB Summary Chronology: Contract NAS7-101—Douglas Aircraft Company," 1963; D. Brainerd Holmes to Robert C. Seamans, "S-IVB Sole Source Procurement with Douglas Aircraft Company," 15 Dec., 1961.
13. Akens, *Saturn Chronology*, pp. 39-40, 43, 50; H. E. Bauer, "Operational Experiences on the Saturn S-IVB Stage," Society of Automotive Engineers Reprint no. 680756, Oct. 1968, p. 1; Mrazek, "Launch Vehicle Systems," vol. 1, pp. 1-2.
14. Ludwig Roth and W. M. Shempp, "S-IVB High Energy Upper Stage and Its Development," Douglas Aircraft Corp., Douglas Paper no. 4040, 1967, pp. 1-2.
15. Bauer, "Operational Experiences," p. 11.
16. Ibid., pp. 2-3; Lange, "Development," p. 17; Roy E. Godfrey, "S-IVB Stage," STAC Conference, pt. 5, pp. 1-2.
17. E. D. Geissler, "Ascent Trajectory Considerations," STAC Conference, pt. 3, pp. 1-13.
18. Earl L. Wilson interview, MDAC, 11 Mar. 1971; MSFC, *Saturn V News Reference*; "S-IVB Fact Sheet"; Charles C. Wood and H. G. Paul, "A Review of Cryogenic Technology Aspects of Space Flight," a paper for the International Cryogenic Engineering Conference, Kyoto, Japan, 1967, unpaged. This paper by Wood and Paul, both MSFC engineers, includes a very informative summary of cryogenic problems of rockets in terms of tankage, orbital maneuvers, low-gravity operations, and insulation.
19. Lange, "Development," p. 8.
20. For specific differences in the S-IVB/IB stage and the S-IVB stages, see, George E. Mueller to NASA Administrator, "Conversion of an SIVB/IB Stage to SIVB/V Configuration," 14 Sept. 1965, and attachments.
21. Bauer, "Operational Experiences," p. 2; Harold E. Bauer interview, MDAC, 8 Mar. 1971; E. Harpoothian, "The Production of Large Tanks for Cryogenic Fuels," Douglas Paper no.

NOTES TO PAGES 165-178

- 3155, 12 Nov. 1964, pp. 3, 10, 19-20, 31. Harpoothian at the time was Chief Engineer, Structures Dept., Development Engineering, Douglas Aircraft Co.
22. Tour of contractor facilities, Mar. 1971; Bauer interview; Harpoothian, "Production of Large Tanks," pp. 4, 6-7, 10, 26, 31; K. H. Boucher, "Saturn Third Stage S-IVB Manufacturing," p. 4; contractor briefing and tour of facilities, McDonnell Douglas and North American Rockwell, Mar. 1971. For examples of typical aerospace construction techniques of the mid-1960s, see Frank W. Wilson and Walter R. Prange, eds., *Tooling for Aircraft and Missile Manufacture* (New York, 1964).
 23. Akens, *Saturn Chronology*, pp. 49, 58; Bauer, "Operational Experiences," pp. 3-5; Boucher, "Saturn S-IVB Manufacturing," p. 4; contractor briefing and tour of facilities, McDonnell Douglas and North American Rockwell, Mar. 1971.
 24. Boucher, "Saturn S-IVB Manufacturing," pp. 6, 9, 11; Harpoothian, "Production of Large Tanks," pp. 6-7, 13-14, 35; Theodore Smith interview, MDAC, 3 Mar. 1971; Bauer, "Operational Experiences," pp. 3, 4.
 25. Bauer, "Operational Experiences," p. 4; Harpoothian, "Production of Large Tanks," p. 14; Roth and Shempp, "S-IVB Development," p. 17; A. C. Robertson and E. L. Brown, "The Development of a Bonded Common Bulkhead for Saturn," Douglas Paper no. 3817, p. 2; Theodore Smith interview.
 26. Robertson and Brown, "Development of Common Bulkhead," p. 2; Theodore Smith interview.
 27. Robertson and Brown, "Development of Common Bulkhead," p. 3. Robertson was from Douglas, and Brown from MSFC. See also Boucher, "Saturn S-IVB Manufacturing," pp. 13-19; Harpoothian, "Production of Large Tanks," pp. 39-44.
 28. Boucher, "Saturn S-IVB Manufacturing," pp. 34-35, 37, 39, 57-58, 60-61. Harpoothian, "Production of Large Tanks," pp. 14, 44; Gerald L. Riggs interview, MDAC, 11 Mar. 1971; tour of MDAC facility, 3 Mar. and 11 Mar. 1971.
 29. Harpoothian, "Production of Large Tanks," pp. 8, 30; Boucher, "Saturn S-IVB Manufacturing," pp. 41-43, 63, 67, 69; Bauer, "Operational Experience," pp. 5-7.
 30. Robert W. Prentice interview, MDAC, 11 Mar. 1971; Harold E. Bauer and Theodore Smith interviews.
 31. Ernst D. Geissler, "Project Apollo Vehicular Plans," a report at a NASA meeting at Langley Research Center, Apr. 1962, p. 4.
 32. Harold Bauer and Theodore Smith interviews.
 33. Glen A. Herstine, "Why Internal Insulation for the Saturn S-IV Liquid Hydrogen Tank?" Douglas Paper no. 1422, Aug. 1964, pp. 1-3.
 34. Ibid., pp. 3-7; Theodore Smith interview; Harpoothian, "Production of Large Tanks," p. 16; Bauer, "Operational Experiences," pp. 8, 11.
 35. Theodore Smith interview; Herstine, "Internal Insulation," pp. 3-7.
 36. Bauer, "Operational Experiences," p. 8; Theodore Smith interview. Specially treated balsa was nevertheless used in some problem areas of the tankage, such as the section where the LH₂ tank joined the common bulkhead. See, for example, D. L. Dearing and R. J. Steffy, "The Significance of Parameters Affecting the Heat Transfer . . . , Douglas Paper no. 3374, June 1965, p. 6 ff.
 37. Bauer, "Operational Experience," pp. 8-9; Boucher, "Saturn S-IVB Manufacturing," pp. 44-46.
 38. Theodore Smith interview.
 39. D. L. Dearing, "Development of the Saturn S-IV and S-IVB Liquid Hydrogen Tank Internal Insulation," Douglas Paper no. 3511, Aug. 1965, pp. 2-3; Boucher, "Saturn S-IVB Manufacturing," pp. 46, 54-55; tour of contractor facilities, Mar. 1971.
 40. Dearing "Development Internal Insulation," pp. 2-3.
 41. MSFC, *Saturn V News Reference*, pp. 5.4-5.6.
 42. Roth and Shempp, "S-IVB Development," pp. 18-19; Harpoothian, "Production of Large Tanks," p. 26; Earl Wilson interview; H. R. Linderfelt interview, McDonnell Douglas, 9 Mar. 1971.
 43. MSFC, *Saturn V Flight Manual*, SA-506, MSFC-MAN-506, 10 June 1969, pp. 6.11-6.12; MSFC, *Saturn V News Reference*, pp. 5.5-5.6.

NOTES TO PAGES 180–192

44. Ibid., 5.6–5.7. As a back-up concept, the S-IVB carried seven extra ambient helium spheres on the thrust structure. Two provided redundancy for LOX tank pressurization, and five provided redundancy for the LH₂ tank (*ibid.*). O. S. Tyson, one of MSFC's resident managers at Douglas during S-IV/IVB development, commented that the availability of significant amounts of helium in this country constituted a special advantage in the U.S space program, since the efficient helium system permitted lower design weights and plumbing for stage pressure systems and other functions. Tyson interview, 3 Mar. 1971.
45. J. D. Shields interview, MDAC, 11 Mar. 1971; Roth and Shempp, "S-IVB Development," p. 19; MSFC *Saturn V News Reference*, pp. 5.5–5.6, 5.8; anonymous MDAC memo to author, 11 June 1976.
46. D. J. Allen and L. G. Bekemeyer, "Design of the Saturn S-IV Stage Propellant Utilization System," Douglas Paper no. 1292, Mar. 1962, pp. 2, 15–16; MSFC; *Saturn V News Reference*, p. 5.9; Lorenzo P. Morata interview, MDAC, 8 Mar. 1971.
47. Morata interview; Allen and Bekemeyer, "Design of PU System," pp. 19, 21. For details of the PU System design and operation, see Allen and Bekemeyer, pp. 3–14, 16–22.
48. MSFC, *Saturn V News Reference*, p. 5.9.
49. MSFC, *Saturn V News Reference*, pp. 5.9–5.10; MSFC, *Saturn V Flight Manual*, SA-506, pp. 6.19–6.20; Robert Prentice interview.
50. Refer to *News Reference* and *Flight Manual*, cited above, *passim*. See also, Godfrey, "S-IVB Stage," STAC Conference, pt. 5.
51. E. A. Hellebrand, "Structures and Propulsion," pt. 2, p. 6.
52. Harpoorthian, "Production of Large Tanks," p. 30; Roth and Shempp, "S-IVB Development," p. 14; Godfrey, "S-IVB," STAC Conference, pt. 5, pp. 5–8.
53. John D. Clark, *Ignition: An Informal History of Liquid Rocket Propellants* (New Brunswick, N.J.: Rutgers Univ. Press, 1972), p. 108; Harold E. Felix interview, MDAC, 9 Mar. 1971.
54. J. B. Gayle, ed., *Investigation of S-IV All Systems Explosion*, NASA TND-563, Sept. 1964, *passim*.
55. Edmund F. O'Connor to Maj. Gen. Samuel C. Phillips, telegram, 9 Feb. 1967; Felix interview; MSFC Saturn V Program Off., *Semiannual . . . Report, January–June 1967*, pp. 33, 52–56, MSFC files; Douglas Aircraft Co., *S-IVB Quarterly Report*, Mar. 1967, pp. 51, 54–55, MSFC files; anonymous MDAC memo to author, 11 June 1976. Loss of S-IVB-503 led to substitution of stage serial numbers 504 for 503N, 505 for 504N, and 506 for 505N. The availability of excess 507 tankage led to its reincarnation as S-IVB-506, with S-IVB-507 and subsequent stages produced as originally planned (Akens, *Saturn Chronology*, pp. 161–162).
56. McDonnell Douglas Corp., "McDonnell Douglas S-IVB Rocket for NASA's Saturn Launch Vehicle," news release, July 1969; MSFC Test Lab., "Historical Report, Jan.–Dec. 1965," pp. 7–8, MSFC files. For description of the automatic checkout concept and its development, refer to Chapter 13.
57. O. S. Tyson interview, MSFC Resident Mgr. at McDonnell Douglas, 3 Mar. 1971.
58. Edmund F. O'Connor to Samuel Phillips (day and month obscured), 1966. Static firing was discontinued, however, later in the program.
59. Theodore Smith, Harold Bauer, and O. S. Tyson interviews.
60. Earl Wilson interview. Nevertheless, the Centaur became a highly reliable upper stage mated to both Atlas and Titan boosters and was used in a wide variety of planetary and Earth-orbital missions.
61. Wilson interview; Theodore Smith interview.
62. Bauer, "Operational Experiences," pp. 2–3; Godfrey, "S-IVB," STAC Conference, part 5, p. 8. Theodore Smith, Harold Bauer, Robert Prentice, and J. D. Shields interviews.

CHAPTER 7

1. Akens, *Saturn Chronology*, p. 33; MSFC, "Saturn V, Project Development Plan," Nov. 1967, pp. 2.2, 3.10, cited hereafter as "Saturn V PDP"; von Braun, "Saturn the Giant" in Cortright, ed., *Apollo Expeditions to the Moon*, pp. 42, 46.
It would have been interesting to learn more of the contractor selection process, but a search for

NOTES TO PAGES 193-207

these records at MSFC in Oct. 1975 was unsuccessful. The S-IC contract negotiations were probably similar to those described for the S-IV and S-II, which the author pieced together from available documents.

2. Milton W. Rosen interviews, NASA, 14 Nov. 1969 and 1 Dec. 1971; Rosen to D. Brainerd Holmes, "Large Launch Vehicle Program," 6 Nov. 1961, with attached report interview, 20 Nov. 1961, JSC files.
3. Von Braun interview, MSFC, 17 Nov. 1971; von Braun, "Saturn the Giant," p. 42; Ernst Geissler interview, MSFC, 7 Sept. 1971; John M. Logsdon, "Selecting the Way to the Moon: The Choice of the Lunar Orbiter Rendezvous Mode," *Aerospace Historian*, 18 (June 1971): 66.
4. George Alexander, "Boeing Faces Unique Fabrication Challenge," *Aviation Week and Space Technology*, 77 (13 Aug. 1962): 52, 59, 63; MSFC, *Saturn V News Reference*, p. 11.4; Boeing Co., Launch Systems Branch, "Contractor Program Procedures," 1966, 1967, 1968; Boeing Co., Launch Systems Branch, "Saturn S-IC, Annual Progress Report," FYs 1964 through 1968.
5. Von Braun interview, 17 Nov. 1971; Matthew Urlaub interview, MSFC, 29 July 1975; Rosen interview, NASA, 1 Dec. 1971.
6. Alexander, "Boeing Faces," pp. 55, 59; Alexander, "S-IC Heavy Tooling Installed at Marshall," *Aviation Week and Space Technology*, 78 (25 Mar. 1963), unpage reprint in SHP files; William Clarke, "Roll Out the Booster," *Boeing Magazine*, 35 (Aug. 1965): 13; William Clarke, "Try This On for Size," *Boeing Magazine*, 35 (Feb. 1965): 9; William Siebel, "Saturn Stands Up," *Boeing Magazine*, 34 (Apr. 1964): 6; MSFC *Saturn V News Reference*, p. 2.5.
For clarification of many details of design, development, and manufacturing of the S-IC stage, the author wishes to acknowledge interviews with Matthew Urlaub and Hans F. Wuenscher, MSFC, 3 Sept. 1971, and Mathias P. Siebel, MSFC, 9 Sept. 1971. Wuenscher and Siebel were both top managers in MSFC's Manufacturing Engineering Lab during this period.
7. MSFC, *Saturn V News Reference*, pp. 2.1-2.5; MSFC, "Saturn V PDP," p. 3.7.
8. Alexander, "Boeing Faces," p. 53; Darrell Bartee, "Hitching Posts for Saturn," *Boeing Magazine*, 35 (Jan. 1965): 6; Whitney G. Smith, "Fabricating the S-IC Booster," AIAA Paper 65-294, July 1965, p. 6; MSFC, "Saturn V PDP," pp. 3.10, 3.18; MSFC, *Saturn V News Reference*, p. 2.4.
9. MSFC, *Saturn V News Reference*, pp. 1.7-1.9; Smith, "Fabrication in S-IC," pp. 5-6; Alexander, "Boeing Faces," p. 53; J. E. Kingsbury, MSFC, to author, 21 June 1976.
10. MSFC, "Saturn V PDP," pp. 3.7-3.15; MSFC, *Saturn V News Reference*, pp. 2.3-2.4, 2.9-2.16; Alexander, "Boeing Faces," p. 55; M. A. Kalange and R. J. Alcott, "Saturn V S-IC Stage Engine Gimbal Actuation System," 18 May 1965, *passim*; William B. Sheil, "Migration to Huntsville," *Boeing Magazine*, 35 (May 1965): 6.
11. Whitney G. Smith, "Fabricating the Saturn S-IC Booster," AIAA Paper no. 65-294, July 1965, p. 1; Alexander, "Boeing Faces," p. 52; Alexander "S-IC."
12. Smith, "Fabricating S-IC," pp. 2-3; Eugene M. Langworthy and Leland Bruce, "Chemical Milling on Apollo and Saturn Gore Segments," Society of Aeronautical Weight Engineers, Technical Paper no. 477, May 1965, pp. 1, 5-7.
13. Alexander, "Boeing Faces," p. 55; Darrel Bartee, "Curves Cured to Order," *Boeing Magazine*, 34 (Nov. 1964): 12-13; Darrel Bartee, "Lunar Look," *Boeing Magazine*, 33 (July 1963): 10-11; Mathias Siebel, "Building the Moon Rocket" (paper presented to meeting of National Machine Tool Builders Association, 3 Nov. 1965), pp. 11-13.
14. William Clarke, "The Uncommon Welder," *Boeing Magazine*, 35 (March 1965): 12; Alexander, "Boeing Faces," p. 59; Alexander, "S-IC"; Smith, "Fabricating S-IC," pp. 4-5; MSFC, *Manufacturing Plan: Saturn V Booster Stage, S-IC 15 January 1963*, vol. 1 (with change inserts through July 1965), pp. 2.1-2.54.
15. Smith, "Fabricating S-IC," pp. 2-4; Siebel, "Building," pp. 18-20; Alexander, "Boeing Faces," pp. 53, 55; Bartee, "Lunar Look," pp. 10-11; MSFC, *Manufacturing Plan*, vol. 1 pp. 3.1-3.40.
16. William Clarke, "Purity Surety," *Boeing Magazine*, 34 (Dec. 1964): 11.
17. Smith, "Fabricating S-IC," pp. 4-5; Alexander, "S-IC."
18. Alexander, "S-IC"; Alexander, "Boeing Faces," pp. 55, 59; Smith, "Fabricating S-IC," pp. 4-5; William Clarke, "Tanks for Saturn," *Boeing Magazine*, 35 (May 1965): 15; William B. Sheil, "Ground Testing a Moon Bird," *Boeing Magazine*, 35 (July 1965): 3, 5; MSFC *Manufacturing Plan*, vol. 2, pp. 7.1-7.302.
19. William B. Sheil, "Countdown to Liftoff," (reprint) *Boeing Magazine*, 1966, pp. 12-13; William

NOTES TO PAGES 209–222

- Clarke, "The Immovable Object." (reprint) *Boeing Magazine*, 1966, p. 3; MSFC, news release, "Saturn V Rocket Booster Test Stand," 5 Aug. 1965; MSFC, *Saturn V News Reference*, p. 8.9.
20. Matthew Urlaub, interview. The author wishes to express his thanks to Mr. Urlaub for permission to review his personal files relating to the S-IC stage. There were the usual design and engineering problems, but no disastrous problems, such as tank explosions or other major setbacks. Representative copies of Urlaub's weekly memos to Dr. Arthur Rudolph, the Saturn V Program Manager, are in the SHP files. See, for example: "S-IC Stage Weekly Status Report," 9 Jan. 1964; 31 Jan. 1964; 14 Feb. 1964; 28 Feb. 1964; 6 Mar. 1964; 9 Apr. 1964. See especially the weekly reports for 13 Oct. 1964, and 4 Nov. 1964.
 21. Elmer L. Field, "The S-II Stage," *Astronautics*, Feb. 1962, p. 35.
 22. T. Keith Glennan, "Memorandum for the Administrator," 19 Jan. 1961.
 23. MSFC, news release, "First Phase S-II Contractor Selection," 12 May 1961.
 24. James E. Webb, "Memorandum for the Record: Selection of Contractors to Participate in Second Phase of Saturn S-II Stage Competition," 8 June 1961.
 25. MSFC, "Minutes of the Phase II Pre-Proposal Conference for Stage S-II Procurement on June 21, 1961," JSC files.
 26. MSFC, *Saturn V PDP*, Nov. 1967, p. 2.2.
 27. D. Brainerd Holmes to Associate Administrator, "Management of Saturn S-II Facilities Program," 27 May 1963; Akens, *Saturn Chronology*, pp. 66–67; Roy Godfrey interview, MSFC, 29 July 1975.
 28. S-II stages, like other Saturn stages, incorporated numerous design variations over the period of their production. This composite description is derived from the following sources: MSFC, *Saturn V News Reference*, pp. 4.1–4.13; MSFC, *Saturn V Flight Manual*, SA-506, 10 June 1969, pp. 5.1–5.30; MSFC, *Saturn V Flight Manual* SA-510, 25 June 1971, 5.1–5.30; MSFC, *Saturn V Project Development Plan*, Nov. 1967, pp. 3.19–3.27; NAA, *Saturn S-II Stage Program Plan*, 1 Apr. 1966; NAA *Manufacturing Plan for Saturn S-II, Stages 16–25*, 14 June 1967, NAA, *Saturn S-II, General Manual*, 1965; NAA, *Saturn S-II Stage: S-II-4 and Subsequent*, Mar. 1963; NAA, *The Saturn S-II*, 14 May 1964; NAA, *Saturn V-Stage II: Power for the Drive into Space*, Aug. 1967; NAR, *Manufacturing Plan for Saturn S-II Stage*, 1 June 1969. Unless otherwise noted, the physical description of the S-II stage structures and systems is based on these documents.
 29. NAA, *The Saturn S-II*, p. 22, NAA, "Saturn S-II: Annual Progress Report," Aug. 1963, pp. 135, 138–40; A. C. van Leuven interview, NAR, 12 Mar. 1971.
 30. Van Leuven interview; H. Raiklen interview, NAR, 11 Mar. 1971; William F. Parker interview, NAR, 8 Mar. 1971; interview, William F. Parker, NAR, 8 Mar. 1971; P. Wickham interview, NAR, 9 Mar. 1971; Richard E. Barton (Dir. of Public Relations, Rockwell International) to author, 18 June 1976, with attached anonymous memo dated 10 May 1976.
 31. For details of the bulkhead assembly sequence, see Tony C. Cerquettini, "The Common Bulkhead for the Saturn S-II Vehicle," NAA Report, 1967; NAR, *Manufacturing Plan*, 1969, pp. 15–25; interviews cited in note 30 above.
 32. For description, photos, and drawings of the foam process, see NAR, *Manufacturing Plan*, 1969, pp. 89–90; NAR, *Manufacturing Development Information Report*, 1968, pp. 45, 55, 83–85. The company also had to devise special phenolic cutter heads to trim the insulation to shape, and use integrated electronic sensors to measure the desired insulation thickness during the cutting procedure. See also interviews with van Leuven and Wickham.
 33. Refer to the sources cited in note 28 above.
 34. Ibid; Raiklen interview; G. A. Phelps interview, NAR, 12 Mar. 1971.
 35. Quoted in "The Toughest Weld of All" *Skyline*, 1968, unpage reprint in SHP files. *Skyline* was the company magazine of North American Rockwell. Other manufacturing details and description from NAA, *Saturn S-II: Annual Progress Report*, 1963, 1964, 1965; NAR, *Manufacturing Development Information Report*, 1968, NAR, *Manufacturing Plan*, 1969; contractor facilities tour and briefing given the author in Mar. 1971; interviews with van Leuven, Wickham, Raiklen, and Parker.
 36. Quoted in "The Toughest Weld of All."
 37. Refer to the sources cited in note 35 above. See also Charles Jordan and Norman Wilson interviews, both of NAR, 2 Mar. 1971. An executive at North American who reviewed a draft of

NOTES TO PAGES 222-230

- the manuscript maintained that over a period of time, the NASA welding concepts were not appreciably superior to North American techniques. Barton to author, with attachment, 18 June 1976.
38. Ray Godfrey and Bill Sneed interviews, MSFC, 28 July 1973.
 39. H. G. Paul to Cline, "S-II Insulation Status," 2 June 1964; NAR, *Saturn S-II: Chronology of Events, 1958-1970* (no date, unpaged). This is a remarkably comprehensive and candid record of NAR's S-II program, comprising a two-inch thick document typed on notebook-size paper. Apparently prepared for management reference.
 40. Samuel C. Phillips to von Braun, 1 Apr. 1965.
 41. Arthur Rudolph to Herman Weidner, 10 May 1965.
 42. Akens, *Saturn Chronology*, pp. 109-120; NAR, *Saturn S-II Chronology*, passim.
 43. Akens, *Saturn Chronology*, pp. 120-121; NAR, *Saturn S-II Chronology*, passim; Samuel Yarchin to William F. Parker, 6 Oct. 1965; Yarchin to Parker, 11 Oct. 1965.
 44. O'Connor to von Braun, "Background Data for Dr. von Braun—Mr. Atwood Meeting," 14 Oct. 1965. Housed in MSFC History Off. in file drawer marked Eberhard Rees, "NAR Organization, S-II Stage." Cited hereafter as Rees files.
 45. Rees to O'Connor, "Meeting on NAA/S&ID Situation," 16 Oct. 1965. Rees files.
 46. Edmund F. O'Connor to Harrison A. Storms, 18 Oct. 1965.
 47. NASA, Hq., Off. of Programs and Special Reports, *Program Review: Apollo*, 16 Nov. 1966, transcription of remarks by General Edmund O'Connor, pp. 81-83.
 48. Dale Myers interview, 17 Mar. 1970
 49. Rees to O'Connor, "Meeting on NAA . . .," 16 Oct. 1965, Rees Files.
 50. George Mueller to J. L. Atwood, 27 Oct. 1965, Rees files.
 51. "Phillips Report," 19 Dec. 1965. The letter to Atwood is included in the complete Phillips Report, housed in the SHP files.
 52. Arthur Rudolph interview, MSFC, 26 Nov. 1968.
 53. Eberhard Rees, "Personal Impressions, Views and Recommendations," memo, 8 Dec. 1965, Rees files.
 54. Eberhard Rees memo, 9 Dec. 1965, attached to 8 Dec. memo cited above.
 55. NAA, news release, 1961; NAA, news release, 25 Jan. 1966.
 56. Robert E. Greer interview, NAR, 5 Mar. 1971. The story of "Black Saturdays" is from an interview with one of Greer's close associates at North American, W. E. Dean, 8 Mar. 1971. Dean and P. Wickham (interview cited above) both commented on enhanced morale.
 57. George E. Mueller to Lee Atwood, 23 Feb. 1966; Harold G. Russell to Gen. Phillips, "S-II-T Program at MTF," 15 Apr. 1966; George F. Esenwein to Dir., Apollo Test/copy to Phillips, "May 25, Attempted S-II-T Full Duration Static Firing," 26 May 1966; transcribed log of phone call, Atwood to von Braun, von Braun daily journal, 27 May 1966 (housed in Alabama Space and Rocket Cr., Huntsville, Ala., cited hereafter as von Braun daily journal); Akens, *Saturn Chronology*, p. 141.
 58. Log of phone calls, Storms to von Braun, 31 May 1966, and von Braun to Gilruth, 1 June 1966, in von Braun daily journal; Akens, *Saturn Chronology*, pp. 142-143; NAR, *S-II Chronology*. See also, E. Mims interview, NAR, 12 Mar. 1971.
 59. Gerald E. Meloy to Robert C. Seamans, "Saturn V S-II-T Stage Explosion," 31 May 1966; George E. Mueller, "Congressional Inquiry (S-II-T)," memo and attached preliminary draft letter, Webb to Sen. Clinton Anderson, 21 Mar. 1967.
 60. Samuel Yarchin to Gen. O'Connor, "Weekly Notes Dr. Rees, S-II Notes for Dr. Rees to Mr. Storms Telecom," 7 Oct. 1966.
 61. Samuel Yarchin to Rees, "Weekly Notes to Storms Telecom," 11 Sept. 1966; O'Connor to Phillips and Rees, "S-II-1 Delays at MTF," 27 Sept. 1966; Frank Magliato to Webb, Seamans, and Shapley, "Static Test of S-II-1," 27 Oct. 1966.
 62. NASA, *Program Review*, 15 Nov. 1966, transcription of remarks by Samuel Phillips, pp. 37-42.
 63. Samuel Phillips to Associate Administrator, "S-II-T Failure Corrective Action," 9 Jan. 1967.
 64. Alibrando to Phillips (memo dealt with MSFC's special technical force visit to Seal Beach), 5 Jan.

NOTES TO PAGES 231–240

- 1967; Phillips to Associate Administrator, "Enclosures: S-II Stage Status," 27 Jan. 1967; NAR, *Saturn S-II Chronology*.
65. Dale Myers interview, NASA, 17 Mar. 1970.
 66. See, for example, Courtney Brooks, James Grimwood, and Loyd S. Swenson, Jr., *Chariots for Apollo: A History of Manned Lunar Spacecraft*, NASA SP-4205 (Washington, 1979); Charles D. Benson and William B. Faherty, *Moonport: A History of Apollo's Launch Facilities and Operations*, NASA SP-4204 (Washington, 1978).
 67. "North American Tries to Advance Under Fire," *Business Week*, 3 June 1967, pp. 154–56, 158.
 68. George E. Mueller to J. L. Atwood, Jan. or Feb. 1967 (date partially obscured).
 69. Arthur Rudolph to John G. Shinkle, TWX, 24 May 1967; Phillips to Ctr. Directors (MSFC, KSC, MSC), TWX, 25 May 1967.
 70. Akens, *Saturn Chronology*, pp. 181, 192, 196, 199.
 71. See, for example von Braun daily journal, for the year 1963.
 72. Parker interview; Sneed and Godfrey interviews.
 73. While much of this involves the personal judgment of the author, the conclusions are based on personal interviews with Matthew Urlaub, Roy Godfrey, Bill Sneed, cited above, and Robert Greer, 5 Mar. 1971. See also Rudolph interview, 26 Nov. 1968. For sympathetic accounts of North American personalities, see Beirne Lay, Jr., *Earthbound Astronauts* (Englewood Cliffs, N.J., 1971), pp. 100–117.

CHAPTER 8

1. Sidney Sternberg, "Automatic Checkout Equipment—The Apollo Hippocrates," *Bulletin of the Atomic Scientists*, 25 (September 1969): 84–87.
2. Paul Alelyunas, "Checkout: Man's Changing Role," *Space/Aeronautics*, Dec. 1965, p. 66.
3. Sternberg, "Automatic Checkout," pp. 84–87.
4. Alelyunas, "Checkout: Man's Changing Role," pp. 66–73.
5. Sternberg, "Automatic Checkout," p. 87. For additional general discussion of Saturn automatic equipment and operations, see, Robert L. Smith, Jr., "Practicalities in Automated Manufacturing Checkout," MSFC, Oct. 1963.
6. D. Morris Schmidt, "Automatic Checkout Systems for Stages of the Saturn V Manned Space Vehicle," a paper presented to IEEE International Conference, New York, Mar. 1965, and published in *Proceedings of the IEEE International Conference*, 13, pt. 4 (1965): 85–86.
7. Ibid., 86; Sternberg, "Automatic Checkout," p. 85; D. Morris Schmidt, "Survey of Automatic Checkout Systems for Saturn V Stages," MSFC, 10 July 1968, p. 3. For procedures at KSC, see Benson and Faherty, *Moonport*.
8. Schmidt, "Automatic Checkout," p. 86; Schmidt, "Survey," p. 4.
9. Schmidt, "Automatic Checkout," p. 87.
10. Ibid., p. 91; Schmidt, "Survey," pp. 6, 27. For discussion of the Saturn I experience, see, Robert L. Smith, Jr., "Automatic Checkout for Saturn Stages," *Astronautics*, February 1962, pp. 46–47, 60; Jack W. Dahnke, "Computer-Directed Checkout for NASA's Biggest Booster," *Control Engineering*, August 1962, pp. 84–87. For the Saturn IB vehicle, see William G. Bodie, *Techniques of Implementing Launch Automation Programs (Saturn IB Space Vehicle System)*, MSFC, NASA TMX-53274, 30 July 1975.
11. Schmidt, "Survey," pp. 7–8; Smith, "Practicalities," p. 3. For additional descriptions of the checkout operations and the equipment involved for each stage, see Schmidt, "Survey." The section on the S-II (pp. 12–17; 33–39) is the most detailed, containing several representative flow diagrams and descriptions of the test operations for all three stages and the IU. See also Frank R. Palm, "A Real Time Operating System for the Saturn V Launch Computer Complex," Huntsville, Ala./IBM, July 1966. MSFC, "Survey of Saturn Stage Test and Checkout Computer Plan Development," 1 June 1966, provides a technical overview of the systems for both the Saturn V and Saturn IB.

NOTES TO PAGES 240-247

12. William Sheil, "Breadboards and D-Birds," *Boeing Magazine*, 35 (October 1965): 10-11; J. W. Moore, J. R. Mitchell, and H. H. Trauboth, "Aerospace Vehicle Simulation and Checkout," MSFC, Apr. 1966; J. R. Mitchell, J. W. Moore, and H. H. Trauboth, "Digital Simulation of an Aerospace Vehicle," MSFC, 9 Mar. 1967.
13. George F. Meister, "The Role of Simulation in the Development of an Automatic Checkout system," Douglas Paper no. 4010, Aug. 1966, p. 19.
14. H. E. Bauer, "Operational Experiences on the Saturn S-IVB Stage," Douglas Paper no. 5268, Oct. 1968, pp. 11-12.
15. Charles Stark Draper, Walter Wrigley, and John Hovorka, *Inertial Guidance* (New York, 1960), pp. 1, 2, 4. Other means of guidance include (1) command guidance: data sent to the vehicle from an operator or computer; (2) homing: may home in on natural radiation or from infrared wavelengths emanating from the target; (3) beam riding: vehicle steers itself along the axis of radar or other system pointed at the target.
Draper was a leading researcher in the field of guidance and control, and his book is a basic treatise in the literature. For a survey of the state of the art during the period of the Saturn program, see Frederick I. Ordway III, James Patrick Gardner, and Mitchell R. Sharpe, *Basic Astronautics* (Englewood Cliffs, N. J., 1962), pp. 366, *passim*.
16. Draper, *Guidance*, pp. 14-18. Important work on gyroscopes was done on both sides of the Atlantic. In the U.S., significant advances were accomplished by Elmer Sperry. See, for example, the exemplary biography by Thomas Parke Hughes, *Elmer Sperry: Inventor and Engineer* (Baltimore, 1971). Aspects of European progress are summarized in Durant and James, *First Steps Toward Space*. For the evolution of long-range aerial navigation in the prewar era, see Monte Wright, *Most Probable Position: A History of Aerial Navigation to 1941* (Lawrence, Kan., 1972).
17. F. K. Mueller, "A History of Inertial Guidance," ABMA, Redstone Arsenal, Ala., 1959, pp. 1, 4, 6, 7. One of the Peenemuende veterans, Mueller was one of the principals who developed the V-2 guidance and control systems.
18. James S. Farrior, "Inertial Guidance, Its Evolution and Future Potential," in Stuhlinger, et al., *Astronautical Engineering*, pp. 150-52.
19. Ibid., pp. 153-54; Ernst A. Steinhoff, "Early Developments in Rocket and Spacecraft Performance, Guidance, and Instrumentation," in Frederick C. Durant III, and George S. James, eds., *First Steps Toward Space*, Smithsonian Annals of Flight, no. 10 (Washington, 1974), pp. 227-85; Wernher von Braun, "Redstone, Jupiter, and Juno," in Emme, ed., *The History of Rocket Technology*, p. 110.
20. Farrior, "Inertial Guidance," p. 154; von Braun, "Redstone," p. 120; IBM, "Instrument Unit Program Review," IBM, Huntsville, Ala., 26 July 1966, p. 3; Oswald H. Lange, "Saturn C-1 Vehicle: Project Development Plan," MSFC, 1 June 1962, p. 4.61.
21. Lange, "Saturn C-1 Vehicle," p. 3.6; von Braun, "Saturn the Giant," in Cortright, ed., *Apollo Expeditions*, p. 52.
22. Lange, "Saturn C-1," pp. 4.14-4.18, 4.57-4.63. In a memo to the author dated 22 June 1976, Walter Haeussermann, who directed MSFC's Astrionics Lab., said that ST-124 components were more like those of the ST-120, used in the Pershing missile.
23. MSFC, *Saturn I Summary*, MSFC, TMX 57401, 15 Feb. 1966 (unpaged).
24. IBM, "Saturn IB/V Instrument Unit System Description and Component Data (Technical Manual)," 1 June 1966, p. 2; IBM, "Program Review," p. 1; *Missile/Space Daily*, 8 Oct. 1965; George Alexander, "Saturn IB Proving Saturn V Control Unit," *Aviation Week and Space Technology*, 18 Apr. 1966, unpage reprint in SHP files.
25. IBM, "Program Review," pp. 5-8, 10, 16; IBM, "Instrument Unit to Navigate Saturn IB's First Flight," news release, 17 Feb. 1966; *Huntsville Times*, 7 Oct. 1965.
26. IBM, "Program Review," *passim*; Ernst D. Geissler and Walter Haeussermann, "Saturn Guidance and Control," *Astronautics*, February 1962, p. 44; Haeussermann, "Guidance and Control of Saturn Launch Vehicles," AIAA Paper 65-304, July 1965, *passim*; James T. Powell, "Saturn Instrumentation Systems," a paper presented at the Third International Symposium on Flight Test Instrumentation, Cranfield, England, June 1964, pp. 6-9.

For clarification of many details of the Instrument Unit, here and in the following pages, the author is indebted to interviews with Luther Powell, Sidney Sweat, Therman McKay, and others, at MSFC, 29 July 1975.

NOTES TO PAGES 248–255

27. IBM, "Instrument Unit," news release; MSFC, Astrionics Lab, "Saturn IB/V Instrument Unit," 1965 (unpaged).
28. IBM, "Saturn IB/V . . . (Technical Manual)," pp. 4–5, 12; MSFC, *Saturn V News Reference*, pp. 7.1–7.2.
29. IBM, "Saturn IB/V . . . (Technical Manual)," pp. 5–9, 15–16; Bendix Corp., "Saturn ST-124-M Inertial Guidance Platform," news release, 21 Feb. 1969, pp. 1–3; Herman E. Thomason, *A General Description of the ST-124-M Inertial Platform System*, MSFC, NASA TN D-2983, Sept. 1965, pp. 44–51.
30. Bendix Corp., "Saturn ST-124-M," p. 2; B. J. O'Connor, "A Description of the ST-124-M Inertial Stabilized Platform and Its Application to the Saturn V Launch Vehicle," Bendix Corp., 26 May 1964. These documents, along with Thomason, *General Description of the ST-124-M*, include drawings, schematics, formulae, and operations of the ST-124. For the theory, equations, and methodology of computation and handling of error signals, see B. J. O'Connor, "An ST-124 Instrument Error Analysis for Saturn S-1 Vehicle," Bendix Corp., Engineering file MT-8094 Issue A (no date).
31. Charles D. LaFond, "First Saturn V Guidance Computer, Data Adapter Prototypes Due at Marshall," *Missiles and Rockets*, 2 Nov. 1964, unpagged copy in SHP files.
32. Ibid., "IBM Computer Will Direct Saturn Orbital Test Flight," June 1966, pp. 3–4.
33. MSFC, *Saturn V News Reference*, p. 7.5; IBM, "IBM Apollo/Saturn Press Information," 1968, unpagged; IBM, "IBM Computer," pp. 3–7; La Fond, "First Saturn V Guidance Computer." For further details of IU theory, formulae, and schematics, see MSFC, Astrionics Lab, "Astrionics System Handbook," 1 Aug. 1965, and change sheets, 15 Aug. 1966; Walter Haeussermann and Robert Clifton Duncan, "Status of Guidance and Control Methods, Instrumentation, and Techniques As Applied in the Apollo Project," a lecture to the Advisory Group for Aeronautical R&D, NATO, Dusseldorf, Germany, 21–22 Oct. 1964. For photos and description of all components, see IBM, "Saturn IB/V Instrument Unit System Description and Component Replacement Data," IBM no. 66–966–0006, Huntsville, Ala., 1 Mar. 1966.
34. IBM, "IBM Apollo/Saturn Press Information," 1968; IBM, "IBM Computer Will Direct," p. 7; La Fond, "First Saturn V Computer"; MSFC, *Saturn V News Reference*, p. 7.4.
35. IBM, "Saturn IB/V . . . (Technical Manual)," pp. 10–11; MSFC, Astrionics Lab, "Saturn IB/V Instrument Unit"; Alexander, "Saturn IB Control Unit." MSFC telemetry rested heavily on experience from the Redstone, Jupiter, and Pershing rocket programs. See, for example, Walter O. Frost and Charles D. Smith, "Saturn Telemetry," MSFC, 1962. For a technical overview of rocket telemetry from the V-2 era through Saturn I, see Otto A. Hoberg and James E. Rorex, "Telemetry Development . . .," in Ernst Stuhlinger, Frederick I. Ordway III, Jerry C. McCall, and George C. Bucker, eds., *From Peenemuende to Outer Space: Commemorating the Fiftieth Birthday of Wernher von Braun, March 23, 1962* (MSFC, 1962), pp. 487–516.
36. MSFC, *Saturn V News Reference*, p. 7.2–7.7; MSFC, Astrionics Lab, "Saturn IB/V Instrument Unit"; Alexander, "Saturn IB Control Unit"; IBM, "Saturn IB/V . . . (Technical Manual)," pp. 5–6.
37. Harvey Heuring and E. Wayne Davis, "The IBM Clean Room Comes of Age," IBM/Huntsville, IBM no. 68-U60-0036, Dec. 1968, pp. 1–3, 5, 12; Heuring, "IBM Mobile Room Lends Flexibility to Apollo Saturn Unit Fabrication," IBM/Huntsville, IBM no. 67-U60-0026, 28 July 1967, pp. 2–5; Heuring, "Methods for Cleaning Electronic Components and Subassemblies," IBM/Huntsville, IBM no. 67-U60-0009, 1967.
38. IBM, "Saturn IB/V . . . (Technical Manual)," pp. 2, 12, 14–15; IBM, "Program Review," p. 12; Alexander, "Saturn IB Control Unit."
39. Sidney Sweat interview, MSFC, 29 July 1975.
40. IBM, "Program Review," pp. 57–64.
41. See, for example, IBM, "Saturn Instrument Unit Mission Contract: Monthly Progress Report for February," 15 Mar. 1966; IBM, "Monthly Progress Report for March," 3 May 1966.
42. O'Connor to Phillips, telephone message transcription, 27 July 1967.
43. Judson A. Lovingood and Ernst D. Geissler, "Saturn Flight-Control Systems," *Astronautics and Aeronautics*, May 1966, p. 100; Helmut J. Horn, "The Iterative Guidance Law for Saturn" paper presented at conference on Aerospace and Navigational Electronics, Baltimore, 27–29 Oct. 1965, p. 9; Walter Haeussermann, "Guidance and Control of Saturn Launch Vehicles," AIAA

NOTES TO PAGES 255–265

- Paper 65–304, July 1965, pp. 5–7; Walter Haeussermann, F. B. Moore, and G. G. Gassaway, "Guidance and Control Systems for Space Carrier Vehicles," in Stuhlinger, et al., *Astronautical Engineering*, p. 163 ff.; MSFC, *Saturn V News Reference*, 7.4–7.5.
44. MSFC, *Saturn V Flight Manual, SA-506*, 10 June 1969, pp. 4.19–4.24, 5.25–5.30, 6.31–6.32.
 45. Ibid.; R. N. Eilerman, "Saturn Auxiliary Propulsion Applications," paper presented at AIAA Meeting, Boston, 29 Nov.–2 Dec. 1966, pp. 1–3, 12–13; R. N. Eilerman telephone interview, 10 Aug. 1972.
 46. Eilerman, "Saturn Auxiliary Propulsion," pp. 1–2, 5–6.
 47. MSFC, *Saturn V News Reference*, pp. 7.4–7.5. Operations of the IU in the Saturn IB missions were quite similar. See, for example, IBM, "Instrument Unit to Navigate Saturn IB's First Flight," news release, 17 Feb. 1966; Alexander, "Saturn IB Control Unit."

CHAPTER 9

1. Wernher von Braun, "Management in Rocket Research," a speech to the Sixteenth National Conference on the Management of Research, held at French Lick, Ind., 18 September 1972. Reprinted in *Business Horizons*, Winter 1962, unpage copy in the SHP files.
2. See, for example, "Director's Weekly Notes," from lab directors and program office directors to von Braun, MSFC/Records Holding Area files; von Braun daily journal, a log of visits, conferences, phone calls, and so on, with memos frequently attached (housed in files of Alabama Space and Rocket Center, Huntsville, Ala.).
3. Akens, *Historical Origins of the George C. Marshall Space Flight Center*, MSFC Historical Monograph no. 1 (Dec. 1960), pp. 71–73; von Braun, "Management"; D. Wyatt interview, NASA, 2 Dec. 1971.
4. See, "Director's Weekly Notes, 11–20–67, Brown," Box III, MSFC/Records Holding Area files. Cited hereafter as MSFC/RHA files.
5. See, "Director's Weekly Notes, 1961–68, MSFC/RHA files, boxes I–IV. The one-page rule is from "Notes, 1–22–62, Haeussermann," Box I; the broom remark is from "Notes, 11–13–61, Gorman," Box I.
6. Quotation from interviews with Mat Urlaub, MSFC, 29 July 1975, and Konrad Dannenberg, MSFC, 30 July 1975. Various individuals from NASA Hq. and MSFC, and the contractors noted the visits by von Braun and their net positive effect. See, for example, interviews with Frank Williams, NASA, 3 Dec. 1971; Wyatt, NASA; Dannenberg, MSFC; Robert Pease, MSFC, 3 Sept. 1971; A. C. van Leuven, NAR, 12 Mar. 1971.
7. Williams interview.
8. Dannenberg interview.
9. Williams interview.
10. Eberhard Rees, "Project and Systems Management," a speech to the XVI World Management Congress, held at Munich, Germany, 25 Oct. 1972, housed in the files of the Saturn V Program Off., cited hereafter as SPO files. For the early years of NASA's managerial development, see Robert L. Rosholt, *An Administrative History of NASA, 1958–1963*, NASA SP-4101 (Washington 1966). Wernher von Braun left in 1970 to take a position at NASA Hq. Eberhard Rees had been one of the early members of the von Braun team in Germany and for many years, both at ABMA and MSFC, had served as deputy director for technical operations in von Braun's office. Rees headed MSFC from 1970 to 1973 and was succeeded by Rocco Petrone, who was followed by William Lucas.
11. Von Braun to Maj. Gen. Don R. Ostrander, 8 Jan. 1960; Abraham Hyatt to the Associate Administrator, NASA, 11 Jan. 1960; Hyatt to the Associate Administrator, 15 Jan. 1960, with attachments.
12. Wyatt, Williams, and Dannenberg interviews, William H. Snead interview, MSFC, 28 July 1973; James W. Wiggins interview, MSFC, 31 July 1973; Normal L. Cropp, "Evolution of Marshall Space Flight Center Program Management Organization," pp. 8–9, SPO files. The Cropp piece is an unpublished document, prepared in 1972, as part of a management study series for the Program Management Directorate. The author was a veteran MSFC executive. See also Oswald H. Lange, "Saturn Systems Management," *Astronautics*, 7 (Feb. 1962): 31, 110.

NOTES TO PAGES 266–276

13. Cropp, "Evolution," pp. 3–4; von Braun, "Management"; Krafft A. Ehricke, "The Peenemuende Rocket Center," *Rocketscience*, 4 (Sept. 1950): 60–61; *Rocketscience*, 4 (Dec. 1950): 81.
14. Von Braun, "Management."
15. Von Braun to Div. Directors and Off. Chiefs, "MSFC Management Policy #1," 16 Aug. 1962; Bill Sneed interview, MSFC, 26 July 1973.
16. Von Braun, "Management"; Rosholt, *Administrative History*, offers a detailed analysis of the reorganization, including organizational charts for both Hq. and center levels.
17. Herman Weidner interview, MSFC, 24 Aug. 1971; von Braun interview, MSFC, 17 Nov. 1971.
18. Dannenberg interview.
19. See, for example, von Braun daily journal, 5 July 1963; 12 July 1963; 31 July 1963; 13 Aug. 1963.
20. Dannenberg interview.
21. William J. Normyle, "A. F. Officers to Bolster Apollo Management," *Aviation Week and Space Technology*, 81 (24 Aug. 1964): 22; anon. memo to Gen. Phillips, NASA, "Press Inquiries Regarding Assignments of NASA Personnel to Air Force Programs," 1 Sept. 1964; anon. memo to Gen. Phillips, NASA, "Response to Senator Symington's Inquiry on Attached Article in *Aviation Week*," 4 Sept. 1964, with attached draft of letter, Webb to Sen. Symington.
22. See Saturn V Program Off., "Saturn V Program Element Plan for Financial and Manpower Management," Oct. 1967. Annex "C" of this document includes the basic guidelines for IO/R&DO relationships. SPO files.
23. Arthur Rudolph interview, MSFC, 26 Nov. 1968.
24. Apollo Program Off., NASA Hq., *NASA-Apollo Program Management*, 1 (Dec. 1967): 3.6–3.12. Up to 1967, no single document, or series of documents, had been issued to lay out the overall management picture in detail. In response to many requests for such information, the Apollo Program Off. authorized a special descriptive series, summarizing the various elements of management that had developed over the years and that were currently in effect. The project ran to 14 separate volumes, covering each of the centers involved in the Apollo-Saturn program, as well as each of the major contractors. Huntsville operations were covered in vol. 3, *Apollo Program Management: MSFC*, SPO files.
25. Cropp, "Evolution," pp. 36–37; George E. Mueller interview, NASA, 27 June 1967; Ray Godfrey interview, MSFC, 29 July 1975.
26. Rudolph interview.
27. Mack Shettles interview, MSFC, 27 July 1973; Rudolph interview.
28. Saturn V Program Control Off., "Saturn V Program Element Plan for Program Management," Aug. 1966, SPO files.
29. Arthur Rudolph, "Saturn V Program Directive #9: Saturn V Program Control System," memo, 1 Apr. 1965, *passim*, SPO files.
30. Saturn V Program Control Off., PEP, "Management," pp. 10, 26, 28, SPO files. There were seven inter-center panels: Flight Evaluation; Instrumentation & Communications; Flight Mechanics; Electrical; Crew Safety; Launch Operations; Flight Operations.
31. D. Brainerd Holmes, Dir. of Manned Space Flight, to Gilruth, von Braun, and Debus, 10 July 1963; Holmes, "Panel Review Board," memo 10 July 1963, copies in SHP files; Apollo Program Off., *NASA . . . Management*, 1: 3.13–3.14; Curt Hughes, "Saturn Management Concept," 20 Nov. 1970, SPO files. This last document is a transcript of a typical presentation made to delegations visiting the Saturn V Program Off. to study its operation.
32. Oswald Lange, "Working Groups within the Saturn Management Plan," memo, 8 Sept. 1960, SHP files; Hughes, "Saturn . . . Concept"; Saturn V Program Control Off., PEP, "Management," p. 12; Saturn V Program Off., "Saturn Management Concept," p. 27, SPO files; Shettles interview.
33. Von Braun interview; Saturn V Program Control Off., PEP, "Management," pp. 13–15; Cropp, "Saturn," p. 8; Hughes, "Saturn . . . Concept"; Rees, "Project Management," p. 14. The anecdote of Rudolph's long meetings was repeated to the author by several staff members of the Saturn V Program Off.
34. Proceedings of the annual program reviews were published by NASA Hq., Off. of Programs & Special Reports. For example: *Program Review: Apollo*, 16 Nov. 1966, SPO files. The text consists

NOTES TO PAGES 277-284

- of transcriptions of the complete remarks made by the participants, accompanied by the charts and slides used in their presentations. For the Apollo Executive Group, see Mueller interview, JSC files; *NASA . . . Management*, 1: 3.6, SPO files.
35. Saturn V Program Control Off., PEP, "Management," p. 10; Hughes, "Saturn . . . Concept"; Shettles interview. For technical managerial reasons, the RMO staffs at Kennedy Space Center and at North American reported directly to Rudolph's office.
 36. Rees, "Project Management," pp. 10, 16-17.
 37. Ibid.
 38. Interview, privileged source. Many contractor personnel remarked on the very close management exercised by NASA, and Marshall in particular, in contrast to the Air Force.
 39. Rees, "Project Management," pp. 16-17.
 40. Transcription of remarks by Gen. Phillips, in NASA Hq., Off. of Programs & Special Reports, *Program Review: Apollo*, 23 Nov. 1964, p. 159.
 41. Transcription of remarks by Lee James, *Program Review*, 23 Nov. 1964, pp. 56-57.
 42. Ibid., pp. 55-57. The battleship test was an early phase in which thick, heavy-duty propellant tanks were used, hence the name. The All Systems Test, as the name implied, involved thorough testing of all related systems: electrical, mechanical, pneumatic, etc.
 43. Ibid.
 44. Rees, "Project Management," p. 17.
 45. Hughes, "Saturn . . . Concept"; Rees, "Project Management," p. 11; Sneed interview; Rudolph interview. Cost-plus-award-fee contracts are a type of incentive involving contractor performance monitored by project personnel and a board. The contractor is judged on various effectiveness factors whose criteria are subject to periodic revisions during the contract, whereas the criteria for the incentive-fee contract are totally spelled out as part of the basic contract.
 46. MSFC, *Saturn V Reliability and Quality Program Plan*, MM 5300.2A, Aug. 1968, SPO files; Rees, "Project Management," pp. 8-9.
 47. Ray Kline, "Memo for Record: Notes on Management Advisory Committee Meeting at Michoud on June 4, 1964," 26 June 1964, SPO files. For the Douglas operation, see L. C. Wilson et al., "Development of Separable Connectors for the Saturn S-IV Stage," Douglas Paper 3552, 1966, pp. 3-8; R. B. Wilson and H. L. Hug, "A Prime Contractor's Reliability Program for Components/Parts for the Douglas S-IVB Stage Project," Douglas Paper 3794, pp. 1-4, copies in SHP files.
 48. Transcription of remarks by Lee James, *Program Review*, 23 Nov. 1964, pp. 58, 60; Rees, "Project Management," pp. 9-10; Rudolph interview.
 49. Hughes, "Saturn Concept"; Rees, "Project Management," p. 11; Sneed interview; Rudolph interview.
 50. Mitchell R. Sharpe interview, 6 Aug. 1973. It would be easy to dismiss such sloganeering, but it was very pervasive and seems to have been taken very seriously. During a tour of contractor facilities in the Los Angeles area in 1971, the author could not help but notice the prominently displayed stickers and placards in engineers' drafting rooms, shop areas, and offices, and the huge banners, proclaiming PRIDE, VIP, etc., hung across the walls of the cavernous buildings where the Saturn V stages were assembled. In cafeterias, and even in executive conference rooms, the coasters for coffee cups and water glasses carried appropriate slogans for "Manned Flight Awareness." For further details of the Manned Flight Awareness program, see Mitchell R. Sharpe, "Manned Flight Awareness—Zero Defects for Man-Rated Space Vehicles," *Industrial Quality Control*, 12 (June 1966): 658-661.
 51. Hughes, "Saturn . . . Concepts."
 52. James Baar and William Howard, *Polaris!* (New York, 1960), pp. 41-42, 49-51.
 53. The Boeing Co., "Management Control Center System," D5-15710, 8 Nov. 1967, pp. 1.3-1.4, SPO files. While this document does not analyze and describe the PCC at MSFC, it was intended as a comprehensive guideline for control centers in general. It includes the philosophies involved, sample charts, and even detail drawings of sample hardware.
 54. Saturn V Program Control Ctr., "Saturn V PCC: Program Control Center," n. d., unpagged, SPO files; Arthur Rudolph, "The Program Manager's Problem," in NASA/MSFC, *First Annual Logistics Management Symposium, September 13 & 14, 1966*, NASA TMX-53566, 16 Jan. 1967, p. 59.

NOTES TO PAGES 284–293

55. Saturn V Program, "Saturn V PCC"; Sidney Johnson interview, MSFC, 26 July 1973.
56. Rees, "Project Management," pp. 15–16; Arthur Rudolph, "Saturn V Management Instruction #14; Saturn V Program Control Ctr.," 15 Apr. 1966, pp. 1–2, SPO files.
57. Rudolph, "Saturn V Management Instruction #14," pp. 3–5, 8–9, 14, SPO files; Rudolph interview; Shettles interview.
58. Johnston interview; William Sheil, "Guidelines for Administrators," *Boeing Magazine*, 36 (January 1966): 6–7.
59. Norman Cropp, "Saturn," p. 8; Baar and Howard, *Polaris*, pp. 221–223. The former is a companion manuscript with Cropp, "Evolution."
60. Kline, memo for record, 1964; R. G. Smith to J. A. Bethay, 12 June 1973, SPO files; Shettles interview.
61. Interviews and demonstrations by Mack Shettles and Merrell Denoon, MSFC, 10 July 1973; Smith to Bethay, 1973; Shettles interview. Arthur Rudolph, Saturn V Management Instruction #19, "Saturn V Resource and Contract Management Reports," memo, 24 Sept. 1965, pp. 2–4; Saturn V Program Control Off., "Saturn V Program Element Plan for Schedule Control System," 1 Oct. 1965, pp. 4–8, SPO files.
62. Thomas E. Jenkins to R. F. Freitag, NASA Hq., "Parts Count Breakdown of the Apollo-Saturn V Space Vehicle," 25 Oct. 1968.
63. Gordon Milliken and Edward J. Morrison, "Management Methods from Aerospace," *Harvard Business Review*, Mar.-Apr. 1973, pp. 6 ff. Based on a NASA study done by the authors, this article summarizes 25 significant methods and includes a significant bibliography of key documents.
64. Tom Alexander, "The Unexpected Payoff of Project Apollo," *Fortune*, July 1969.
65. The significance of these various influences on Saturn management is largely drawn from observations and conversation with personnel of the Saturn V Program Office during the summer of 1973, when the author was associated with the office as part of the NASA-American Society for Engineering Education, Faculty Fellowship Program. See also, Cropp, "Saturn," *passim*.
66. Lee James interview, MSFC, 21 May 1971.
67. Von Braun memo, 16 Aug. 1962.
68. Kline memo, 26 June 1964.
69. Von Braun to O'Connor (IO) and Weidner (R&DO), "R&D Operations and Industrial Operations: Charters and Guidelines for Cooperation," 19 Feb. 1965, SPO files, See also Saturn V Program Control Off., "Saturn V Program Element Plan for Financial and Manpower Management," Oct. 1967, SPO files.
70. Mack W. Shettles, "Exertion of Authority by Saturn V Staff Offices," Management Research Paper, Sch. of Industrial Management, Georgia Inst. of Technology, Dec. 1967, pp. 24–25, 31–43, SPO files.
71. Interviews with Mack Shettles, Herman Weidner, Sid Johnston, and Bill Sneed were particularly helpful to the author in understanding the basic features of the Saturn management system.
72. Saturn V Program Control Off., PEP, "Management," p. 9.
73. Sneed interview; *Marshall Star*, 3 Nov. 1965. Direct quote supplied by Bill Sneed, from notes taken at the time.
74. Shettles interview; Sneed interview. Copies of various presentations are housed in the files of the Saturn V Program Control Off. Direct quote supplied by Bill Sneed, from notes taken at the time.
75. This chapter is based on a revised version of Roger E. Bilstein, "The Saturn Management Concept," NASA CR-129029, 1 June 1974, prepared when the author participated in the 1973 NASA-American Society for Engineering Education, Faculty Fellowship Program. See also Konrad K. Dannenberg, "Management Philosophies as Applied to Major NASA Programs," Report by the University of Tennessee Space Institute, NGR 43-001-116, Oct. 1974; Lee B. James, "Management of NASA's Major Projects," July 1973.

CHAPTER 10

1. George Mueller, in NASA, *First Annual Logistics Management Symposium, 13–14 September 1966*, NASA, TMX-53566, 16 Jan. 1967, p. 9; Arthur Rudolph, in NASA, *Logistics Management*, p. 60.

NOTES TO PAGES 294-307

2. Von Braun, in NASA, *Logistics Management*, p. 3; O'Connor in *Logistics Management*, p. 7; John C. Goodrum and S. M. Smolensky, "The Saturn Vehicle Logistics Support System," AIAA Paper 65-268, Apr. 1965, pp. 5-8 *passim*.
3. Goodrum and Smolensky, "Saturn Logistics," p. 2; Mueller, in NASA, *Logistics Management*, p. 8.
4. Rudolph, in *Logistics Management*, p. 59.
5. John C. Goodrum interview, MSFC, 31 Aug. 1971.
6. Rudolph, in NASA, *Logistics Management*, pp. 58-59.
7. O'Connor, in *Logistics Management*, pp. 6-7.
8. Rudolph, in *Logistics Management*, pp. 59-60.
9. Goodrum and Smolensky, "Saturn Logistics," p. 4; Goodrum interview; Carl D. DeNeen interview, MSFC, 23 Aug. 1971. Logistical considerations at KSC are further discussed in Kurt H. Debus, "Logistical Support for Launch Site Operations" in NASA, *Logistics Management*, pp. 12-17. See also the voluminous KSC logistics manual, *Apollo/Saturn Logistics Support Requirements Plan*, NASA, Kennedy Space Center, K-AM-02, 31 May 1966. This document includes guidelines for logistical interface and changeovers at the Cape.
10. Goodrum and Smolensky, "Saturn Logistics," pp. 16-17, 19; Goodrum interview. For a discussion of some of the more technical considerations in transporting and handling cryogenic propellants, see also R. D. Walter and B. J. Herman, "Saturn Vehicle Cryogenic Programs," Cryogenic Engineering Conf., Rice Univ., Houston, 23-25 Aug. 1965.
11. Rudolph, in NASA, *Logistics Management*, pp. 58, 60.
12. Konrad Dannenberg interview, MSFC, 30 July 1975.
13. Akens, *Saturn Chronology*, p. 6; Goodrum and Smolensky, "Saturn Logistics," pp. 14-15; MSFC, Saturn Systems Off., "Saturn C-1, Project Development Plan," 10 Aug. 1961, p. 4.91, cited hereafter as MSFC, "Saturn C-1, PDP"; Georg von Tiesenhausen, "Ground Equipment to Support the Saturn Vehicle" a paper presented at a meeting of the American Rocket Society, Washington, D.C., 5-8 Dec. 1960, pp. 1-2; Georg von Tiesenhausen, "Saturn Ground Support and Operations," *Astronautics*, 5 (Dec. 1960): 33, 78.
14. Tiesenhausen, "Saturn Operations," p. 33; William A. Mrazek, "The Saturn Project," *Astronautics*, 5 (July 1960): 75; Akens, *Saturn Chronology*, p. 9; MSFC, "Saturn C-1 PDP," p. 4.90.
15. Akens, *Saturn Chronology*, p. 58; Goodrum and Smolensky, "Saturn Logistics," p. 13; William B. Sheil, "Big Wheels Carry Big Bird," *Boeing Magazine*, 34 (Dec. 1964): 6-7. For details of the steering actuators for each modular pair of wheels, see also John Carlson, "Steering Mechanism for Saturn Transporter," *Ground Support Equipment*, Jan.-Feb. 1964, pp. 32-33.
16. Goodrum and Smolensky, "Saturn Logistics," p. 15; "Saturn S-IVB Hints at Future Problems in Transport, Handling," *Missiles and Rockets*, 10 (16 Oct. 1961): 32-33; R. W. Prentice, "Transportation of Douglas Saturn S-IVB Stages," Douglas Paper no. 3688, p. 6.
17. Prentice, "Transportation of S-IVB," pp. 3, 5, 19-20; H. E. Bauer, "Operational Experiences on the Saturn S-IVB Stage," Douglas Paper no. 5268, Oct. 1968, p. 10.
18. Goodrum and Smolensky, "Saturn Logistics," pp. 11-13; briefing and tour of contractor facilities, North American Rockwell, Mar. 1971.
19. Franklin L. Thistle, "Rocketdyne: The First 25 Years," Rocketdyne, 1970, unpage; Akens, *Saturn Chronology*, pp. 189, 212; Goodrum and Smolensky, "Saturn Logistics," p. 14. For illustrations and descriptions of the vast array of handling and auxiliary equipment for servicing and checkout of the Saturn V, see NASA-MSFC, *Saturn V Launch Vehicle Ground Support Equipment Fact Booklet*, NASA Technical Manual, MSFC-MAN-100, 25 Aug. 1967.
20. MSFC, "Saturn C-1, PDP," p. 4.93; Akens, *Saturn Chronology*, pp. 14, 16; Carl D. DeNeen interview; briefing and tour of MSFC barges and facilities with Carl L. Pool, MSFC, 26 Aug. 1971.
21. MSFC Historical Off., "History of the George C. Marshall Space Center From January 1 to June 30, 1961," vol. 1, MHM-3, Nov. 1961, pp. 51-52; "... July 1 to December 31, 1961," vol. 2, MHM-4, Mar. 1962, 24-25; Carl L. Pool, briefing.
22. Akens, *Saturn Chronology*, *passim*; Pool, briefing; Carl D. DeNeen interview; MSFC, *Saturn IB News Reference*, Sept. 1968, pp. 8.2 *passim*; Goodrum and Smolensky, "Saturn Logistics," pp. 15-16, fig. 12.
23. William A. Mrazek, "The Saturn Launch Vehicle Family," lecture at Univ. of Hawaii, June 1966, p. 7.

NOTES TO PAGES 307-317

24. Bauer, "Operational Experiences," p. 10; "Saturn S-IV Hints at Future Problems," p. 32; John Goodrum interview.
25. William B. Sheil, "Up the River to the Moon," *Boeing Magazine*, 34 (Sept. 1964): 6-7; Pool briefing; De Neen and Goodrum interviews.
26. MSFC, *Saturn IB News Reference*, p. 8.13.
27. Robert W. Prentice interview, MDAC, 11 Mar. 1971; Goodrum and Smolensky, "Saturn Logistics," *passim*.
28. Akens, *Saturn Chronology*, pp. 17-18; H. L. Lambert, "Can Saturn S-IV be Piggy-backed by C-133 from Santa Monica to Canaveral," *Society of Automotive Engineers Journal*, 69 (Dec. 1961): 70-71; Frank G. McGuire; "Airship Studied as Booster Carrier," *Missiles and Rockets*, 12 (4 March 1963): 16; "Saturn S-IV Hints at Future Problems," pp. 32-33.
29. H. E. Bauer, "Operational Experiences," pp. 10-11; Julian Hartt, *Mighty Thor* (New York, 1961), *passim*.
30. Donald L. Stewart interview, MSFC, 1 Aug. 1972. Formerly an engineer at Boeing, Stewart came to MSFC in 1961 and became associated with logistics management, particularly the Guppy operations. Conroy's final acquisition of the Stratocruisers evidently came from Transocean Airlines, an active nonscheduled airline from 1946 to 1960, when it went bankrupt. See, for example, Bill Eaton, "Transocean's Stratocruisers Languish," *Journal of the American Aviation Historical Society*, 9 (Fall 1964): 229-230.
31. Goodrum interview; Prentice interview; Stewart interview.
32. *Jane's All the World's Aircraft* (London, 1909—), for 1955/56 and 1971/72, respectively. Details of the conversion job are given in Harold D. Watkins, "Boeing 377 Undergoes Flight Test," *Aviation Week and Space Technology*, 78 (24 June 1963): 80-81, 84.
33. Bauer, "Operational Experiences," p. 11; R. W. Prentice, "Transportation of Douglas Saturn S-IVB Stages," Douglas Paper no. 3688, Nov. 1965, pp. 14-15.
34. John M. Conroy to von Braun, Enclosure A, 29 Oct. 1962; Stewart interview; Goodrum interview.
35. John M. Conroy to von Braun, 29 Oct. 1962.
36. D. Brainerd Holmes to Robert Seamans, 25 Apr. 1963.
37. MSFC Historical Off., *History of the George C. Marshall Space Flight Center—January 1-June 30, 1963*, Nov. 1963, pp. 1, 4, 57-58; *July 1-December 31, 1963*, vol. 2, July 1964, 47. The contracts included a complicated pay schedule, formulated as to mileage and time, ranging from \$5.80 to \$3.95 per kilometer (Conroy to von Braun, 29 Oct. 1962). By Nov. 1968, NASA had paid Aero Spacelines a total of \$11 591 633 in contracts. (Akens, *Saturn Chronology*, p. 203); additional Guppy flights noted in Akens, *Saturn Chronology*, pp. 65, 71-73.
38. Prentice, "Transportation of S-IVB," p. 15; Goodrum and Smolensky, "Saturn Logistics," p. 10.
39. Conroy to von Braun, 29 Oct. 1962; Robert Freitag to von Braun, 3 Feb. 1964.
40. D. L. Stewart personal files, notes and memoranda, 2 Feb. 1964; "B-36 May Tote Saturn Stage," *Huntsville Times*, 1 Dec. 1963; J. H. Overholser, Aero Spacelines, to Maj. Gen. Samuel C. Phillips, Deputy Dir. Apollo Program, NASA, Washington, D.C., 9 May 1964. See also, "Aero Spacelines Seeking Options to Buy Saunders-Roe Flying Boats," *Aviation Week and Space Technology* (20 Jan. 1964), 34.
41. Telephone interview with Donald L. Stewart, 11 Aug. 1972.
42. Harold D. Watkins, "Larger Guppy Aimed at S-IVB Transport," *Aviation Week and Space Technology*, 82 (19 Apr. 1965): 43, 45; Harold D. Watkins, "Super Guppy to Make First Flight August 25," *Aviation Week and Space Technology*, 83 (23 Aug. 1965): 42-43; Stewart interview; Earl D. Hilburn, Deputy Assoc. Administrator, NASA Hq., to Robert H. Charles, Asst. Secretary of the Air Force, 20 May 1965. For details on the C-97J, see *Jane's* for 1955/56.
43. John C. Goodrum to Maj. Gen. Samuel C. Phillips, TWX, 4 Mar. 1966; Akens, *Saturn Chronology*, pp. 135-136.
44. Prentice, "Transportation of S-IVB," pp. 15-19; Richard W. Trudell and Keith E. Elliott, "The Dynamic Environment of the S-IV Stage During Transportation," Douglas Paper no. 1780, 4 Dec. 1963, pp. 28, 30, 34, 43.
45. Stewart interview.
46. De Neen interview; Stewart interview; Stewart personal file, notes and photos. See also "Super

- Guppy," *Product Engineering*, 8 Nov. 1965, p. 75; Harold E. Felix interview, MDAC, 9 Mar. 1971; Ruth Jarrell, comp., *A Chronology of the Marshall Space Flight Center, January 1-December 31, 1967*, MSFC, Apr. 1970, p. 108; Akens, *Saturn Chronology*, pp. 162, 170, 226.
47. Leo L. Jones, comp., *A Chronology of the Marshall Space Flight Center January 1-December 31, 1968*, MSFC, Feb. 1971, pp. 21, 83, 102-104; MSFC photo archives and *Marshall Star*, 1970-1972.
 48. *New York Times*, 31 July 1965; Watkins, "Super Guppy," p. 43; "Johnston to Head Aero Spacelines," *Aviation Week and Space Technology*, 83 (20 Nov. 1967): 30. Conroy left the company in 1967 to engage in other aircraft conversion operations. The original firm built three more Guppies. For details, see Roger E. Bilstein, "Aircraft for the Space Age: The Guppy Series of Transports," *Aerospace Historian*, 21 (Summer 1974): 85-86.
 49. Goodrum interview.

CHAPTER 11

1. F. A. Speer, "Saturn I Flight Test Evaluation," AIAA Paper 64-322, July 1964, pp. 1, 8.
2. MSFC, *Saturn I Summary*, MSFC, TMX-57401, 15 Feb. 1966 (unpaged).
3. For comments on Highwater, see interviews with von Braun, MSFC, 30 Nov. 1971; Stuhlinger, MSFC, 25 Aug. 1971; Bucher, MSFC, 30 Aug. 1971.

Each Saturn I flight, SA-1 through SA-10, was preceded by a technical summary including miscellaneous diagrams, mission profile details, and operational highlights. See, for example, MSFC, *Technical Information Summary, SA-1*, and subsequent. In addition, each of the Saturn I missions received an exhaustive postmission analysis, best summarized by the "Saturn Flight Evaluation Working Group," which operated out of the Flight Evaluation and Operational Studies Div., Aero-Astroynamics Lab. See, for example, MSFC, *Saturn Flight Evaluation Working Group, Saturn AS-1 Flight Evaluation*, a generic title, respectively, for the SA-1, SA-2, and SA-3 missions. For missions SA-4 through SA-10, see MSFC, *Saturn Flight Evaluation Working Group, Results of the Fourth Saturn I Launch Vehicle Test Flight*, SA-4, and subsequent. All of these documents may be consulted in the files of the MSFC Historical Off. All launches made from Cape Kennedy (or Cape Canaveral, as it was known prior to 1963) are conveniently tabulated and summarized in William A. Lockyer, Jr., ed., *A Summary of Major NASA Launchings, Eastern Test Range and Western Test Range: October 1, 1958 to September 30, 1970*, rev. ed., Historical Report no. 1 (Kennedy Space Center, Fla., 1970). Files of the Saturn History Project include general as well as specific information on the Saturn I series. Mission highlights of each Saturn I launch are recapitulated in MSFC, *Saturn I Summary*, 15 Feb. 1966. See also B. E. Duran, "Saturn I/IB Launch Vehicle Operational Status and Experience," Society of Automotive Engineers, Paper no. 680739, 1968. James P. Lindberg, "Saturn I Flight Test Evaluation," MSFC, 1966, includes mission summaries and technical diagrams. Propulsion aspects are treated more specifically in B. K. Heusinger, "Saturn Propulsion Improvements," *Astronautics and Aeronautics*, 2 (Aug. 1964): 20-25. For information more specifically related to the Block I vehicles, see O. Hoberg, "Saturn SA-1 Flight and Its Instrumentation," MSFC, Apr. 1966; F. A. Speer, "Saturn I Flight Test Evaluation," AIAA Paper 64-322, July 1964; Fernando S. Garcia, *An Aerodynamic Analysis of Saturn I Block I Flight Test Vehicles*, MSFC: NASA TND-20002, Feb. 1964. Unless otherwise noted, information for the composite summaries of the Saturn missions was abstracted from the documents noted above.

4. For description and discussion of the Block II series, see MSFC, *Saturn I Summary*; Heusinger, "Saturn Propulsion Improvements"; Lindberg, "Saturn I . . . Evaluation"; Duran, "Saturn I/IB . . . Experience."
5. Carl T. Huggins, "Saturn Television System for SA-6," MSFC, Internal Note, M-ASTR-IN-63-6, 25 Feb. 1963, pp. 1-13.
6. Lindberg, "Saturn I . . . Evaluation," pp. 4-6; A. J. Davis and P. L. Hassler, "Saturn IB Inflight Photographic Instrumentation System," MSFC, Sept. 1966.
7. Lindberg, "Saturn I . . . Evaluation," p. 9.
8. Duran, "Saturn I/IB . . . Experience"; MSFC, *Saturn I Summary*.
9. MSFC, *Saturn I Summary*. For discussion of the IU, see Chap. 8.

NOTES TO PAGES 330–338

10. Arthur C. Clarke, *The Promise of Space* (New York, 1968), pp. 83–84.
11. Ibid.; Fred L. Whipple, *Earth, Moon, and Planets* (Cambridge, Mass., 1963), pp. 71, 74; Wernher von Braun, *Space Frontier* (New York, 1967), pp. 90–91, 184–185.
12. Ernst Stuhlinger, "Meteoroid Measurements with Project Pegasus," paper presented at Northeast Electronics Research and Engineering Meeting, Boston, 4 Nov. 1965, pp. 1–2; NASA, *The Meteoroid Satellite Project Pegasus, First Summary Report*, NASA TND-3505, Nov. 1966, pp. 1–2; von Braun, *Space Frontier*, p. 91. The problem of meteoroid penetration of booster tank walls, as well as spacecraft, was also noted in interviews with von Braun, NASA, 30 Nov. 1971; Stuhlinger, MSFC, 25 Aug. 1971; Bucher, MSFC, 30 Aug. 1971. Stuhlinger had been chief of MSFC's Space Science Lab; Bucher was a top aide during the Pegasus project. For discussion of meteoroid research, see also "Satellites: Manned and Unmanned, Report of Conference at Virginia Polytechnic Institute," *Science*, 22 Nov. 1963, p. 1091; Joseph H. Wujek, "Experiments in Space," *Electronics World*, July 1965, p. 48. Although many scientific books and journals refer to "micrometeoroids," NASA consistently used the term "meteoroid," with diminutive size inherently implied. The author has followed NASA's style in this case.
13. NASA, *Meteoroid Satellite*, pp. ix, 2–3; M. Getler, "Hope Grows for Follow-on Pegasus," *Missiles and Rockets*, 22 Feb. 1965, p. 15; C. D. La Fond, "Meteoroid Detection Satellite Mock-up Shown," *Missiles and Rockets*, 24 June 1963, p. 32; William G. Johnson interview, MSFC, 23 Aug. 1971. Johnson was the Project Manager for Pegasus.
14. NASA, *Meteoroid Satellite*, pp. 4, 29–31; Stuhlinger, "Meteoroid Measurements," p. 7; "Measuring Meteoroids: Orbiting Pegasus Launched," *Time*, 26 Feb. 1965, p. 58.
15. NASA, *Meteoroid Satellite*, pp. 10, 27, 35–37; Getler, "Hope Grows," p. 15; Stuhlinger, "Meteoroid Measurement," pp. 4–9; La Fond, "Meteoroid Detection," p. 32.
16. La Fond, "Meteoroid Detection," pp. 32–33; Akens, *Saturn Chronology*, p. 92.
17. Akens, *Saturn Chronology*, pp. 89, 97, 104.
18. Getler, "Hope Grows," pp. 14–15; NASA, *Meteoroid Satellite*, pp. 59–60; Akens, *Saturn Chronology*, pp. 100, 103–104; "First Ten Lives of Saturn I," film, MSFC, Serial no. M-206.
19. Raymond M. Watts, Jr., "Pegasus Satellite Flies," *Sky & Telescope*, 29 (Apr. 1965): 210; Raymond M. Watts, Jr., "Pegasus 3," *Sky & Telescope*, 30 (Oct. 1965): 215.
20. Getler, "Hope Grows," pp. 14–15; Watts, "Pegasus Satellite," p. 210; NASA, *Meteoroid Satellite*, pp. 60–62; Stuhlinger, "Meteoroid Measurements," pp. 9–10; "First Industry-Built Saturn I Puts Pegasus-2 in Precise Orbit," *Aviation Week and Space Technology*, 80 (31 May 1965): 2; "S-I Readied for Pegasus 2 Launch," *Aviation Week and Space Technology*, 80 (24 May 1965): 25.
21. Akens, *Saturn Chronology*, pp. 108, 110; "Meteoroid Program May Be Expanded," *Missiles and Rockets*, 31 May 1965, p. 17.
22. "Measuring Meteoroids," *Time*, 26 Feb. 1965, p. 58; comments by von Braun and Mueller in "Meteoroid Program," *Missiles and Rockets*, p. 17.
23. "First Industry-Built Saturn I," *Aviation Week*, p. 21; NASA, *Meteoroid Satellite*, p. 63.
24. Akens, *Saturn Chronology*, pp. 112–114, 126.
25. NASA, *Scientific Results of Project Pegasus: Interim Report*, NASA, TMX-53629, 3 July 1967, pp. vii, 25, 27–31.
26. Phillips to von Braun, telegram, "Subject: Gemini Rendezvous with Pegasus," 28 May 1965; NASA, *Meteoroid Satellite*, p. 64; Watts, "Pegasus 3," p. 215; Lockyer, *Summary of Major NASA Launchings*, p. 121.
27. The quotation is from Frank W. Anderson, Jr., *Orders of Magnitude: A History of NACA and NASA, 1915–1976*, NASA SP-4403 (Washington, 1976), p. 55. Skepticism about the Saturn I launches, and Highwater in particular, was expressed to me by NASA employees at Huntsville and elsewhere. The persistence of such allegations prompted me to question several Saturn I project managers; they tended to reaffirm the presumed value of Highwater and later Block II launches in particular. Von Braun's response seemed to be the most candid. See von Braun interview, NASA, 30 Nov. 1971.
28. This was the consensus expressed in interviews with William Johnson, head of the project; Ernst Stuhlinger, former Dir. of the Space Sciences Lab.; and Stuhlinger's deputy, George Bucher.
29. Gerhard Heller interview, MSFC, 3 Sept. 1971; von Braun interview, MSFC, 30 Nov. 1971.
30. Information concerning Saturn IB missions AS-201 through AS-205 can be found in the continuing series of reports, such as: MSFC, *Saturn Flight Evaluation Working Group, Results of*

NOTES TO PAGES 338–352

*the First Saturn IB Launch Vehicle Test Flight, AS-201, and subsequent, housed in the files of the MSFC Historical Off. In addition, see Lockyer, A Summary of Major NASA Launchings (cited for the Saturn I mission narratives); NASA-MSFC, *Saturn IB News Reference*, Sept. 1968; and Duran, "Saturn I/IB . . . Experience." Unless otherwise noted, information for the composite summaries of the Saturn IB launches was compiled from the assorted documents noted above.*

31. Savage to Dir., Apollo Program, 3 Mar. 1966; Kurt Debus to Gen. Phillips, 8 June 1966.
32. Davis and Hassler, "Saturn IB Photo System," pp. 90–96; MSFC, *Saturn IB News Reference*, *passim*.
33. Akens, *Saturn Chronology*, p. 138; Duran, "Saturn IB . . . Experience"; Eberhard Rees to Gen. Phillips, 6 June 1966.
34. MSFC, *Saturn IB News Reference*, pp. 12.3–12.4; MSFC, "AS-203 Technical Information Summary," 14 June 1966.
35. For extended discussion of the fire and its aftermath, see Brooks, Grimwood, and Swenson, *Chariots for Apollo*.
36. Akens, *Saturn Chronology*, p. 163; Lockyer, *Summary of Major NASA Launchings*, p. 117.
37. MSFC, *Saturn IB News Reference*, pp. 12.5–12.6; Lockyer, *Summary of Major NASA Launchings*, p. 123; KSC, "Apollo/Saturn Consolidated Instrumentation Plan for AS-204/LM-1," K-IB-029/4, 16 Oct. 1967; NASA, "Press Kit: Apollo 5," 11 Jan. 1968, pp. 20–21; NASA, "Apollo 5 Pre-Launch Press Conference," 21 Jan. 1968, pp. 8–9; NASA, "Apollo 5 Post-Launch Press Conference," 21 Jan. 1968, pp. 8–9; NASA, "Apollo 5 Post-Launch Press Conference," 22 Jan. 1968.
38. Apollo News Ctr., "Apollo 7 Mission Commentary," 11 Oct. 1968, pp. 12.1–12.4, 22.1, JSC files.
39. Lockyer, *Summary of Major NASA Launchings*, p. 126; Leo C. Jones, comp., *A Chronology of the George C. Marshall Space Flight Center January 1–December 31, 1968*, MSFC, MHR-8, Feb. 1971, pp. 109–13; NASA, "Press Kit: Apollo 7," 6 Oct. 1968, pp. 8, 29, 33–34.

CHAPTER 12

1. Quoted in James J. Haggerty, "Apollo 4: Proof Positive," *Aerospace*, 5 (Winter 1967): 4.
2. Haggerty, "Apollo 4," p. 3; NASA, "Apollo 4 Pre-Launch Press Conference," 8 Nov. 1967, pp. 3–4, 9–10.
3. Webb to R. Cargill Hall, 20 Dec. 1974.
4. Sharpe, "Saturn and All-up Flight Testing: Historical Note, Saturn History Project," Jan. 1974, p. 2.
5. NASA, Off. of Manned Space Flight, "Apollo Flight Mission Assignments," 9 Apr. 1963, pp. 5–7, cited in Sharpe, "Saturn." Mueller interview, NASA, 21 Apr. 1971, copy in JSC files.
6. Mueller to Directors, MSC, LOC, MSFC, teletype, 1 Nov. 1963.
7. R. B. Young to Mitchell R. Sharpe, 11 Jan. 1974; Walter Haeussermann interview, 14 Dec. 1973; Frank Williams to M. R. Sharpe, 20 Feb. 1974; Eberhard Rees to Robert Sherrod, 4 Mar. 1970; Dieter Grau to M. R. Sharpe, 12 Dec. 1973. The conservative approach to launch vehicle testing is inherent in all of the sources noted above. The decision of von Braun and Rees to back Mueller, as the boss, was noted by Bob Young, who also remembered continuing reluctance by some MSFC chieftains. The decision by von Braun to back up Mueller, forcefully overriding his staff, was also remembered by another individual from the senior management level (privileged source).
8. Von Braun to Mueller, 8 Nov. 1963.
9. Transcribed telephone conversation appended to von Braun daily journal, 8 Nov. 1963, ASRC files.
10. Arthur Rudolph interview, MSFC, 14 Dec. 1973.
11. Harvey Hall to Gen. Phillips, 10 Apr. 1964.
12. NASA, "Roll-out Ceremony: Saturn V Facility Vehicle (500-F)," 25 May 1966; Arthur Rudolph, "Operational Experience with the Saturn V," AIAA Paper 68–1003, Oct. 1968, p. 3.
13. Phillips to Ctr. Directors (MSC, MSFC, KSC, GSFC), teletype, 25 July 1967.
14. Phillips to Mueller, "AS-501 as Apollo 4," 4 May 1967; L. E. Day to Gen. Phillips, "Brief

NOTES TO PAGES 352–363

- Summary of Status for Items on Agenda for AS-501 Meeting at KSC Friday, March 10, 1967"; anon., "Minutes of March 10, 1967 Meeting at KSC to discuss AS-501"; Gen. O'Connor to Gen. Phillips, "KSC-501 meeting," memo of call, 16 Mar. 1967.
15. J. J. O'Connor, "SA-501 Program Managers Pre-Flight Review—Case 330," 2 June 1967; J. J. O'Connor to Gen. Phillips, "Working Note—S-IC-8 Weld Cracks," 15 June 1967; Gen. Phillips, to Directors, MSFC, MSC, KSC, "Changes Relating to Apollo 4," 16 June 1967.
 16. NASA, "Press Conference: Roll-out of Apollo 4 (Apollo/Saturn 501)," KSC, 26 Aug. 1967.
 17. See, for example, Schneider and Wagner, "Memorandum to Maj. Gen. S. C. Phillips on Purging of the S-II LOX Fill and Drain Line," 1 Sept. 1967.
 18. Bill Schneider to Gen. Phillips, "Helium Pressure Regulator in the Pneumatic Console," memo of call, 10 Oct. 1967; Rudolph, "Operational Experience," p. 4.
 19. Bart J. Slattery, Jr., to von Braun, 25 Oct. 1967.
 20. Gen. Phillips to the Deputy Administrator, "Apollo 4 Launch Schedule," 2 Nov. 1967.
 21. Rudolph, "Operational Experience," p. 4.
 22. Miscellaneous data and comparisons were culled from the following sources: MSFC, Public Affairs Off., Release 67-217, 30 Oct. 1967; NASA, Off. of Public Information, "Current News," 7 Nov. 1967; NAR, "This is the First of the Big Shots," 1967; *Houston Post*, 17 Sept. 1967; James J. Haggerty, "Apollo 4: Proof Positive," *Aerospace*, 5 (Winter 1967): 3-7; Gene Bylinsky, "Dr. von Braun's All-Purpose Space Machine," *Fortune*, 75 (May 1967): 142-149.
 23. Von Braun daily journal, von Braun itinerary, Cape Kennedy, Fla., 6-9 Nov. 1967; W. C. Schneider, NASA Hq. to multiple addressees, 9 Nov. 1967; NASA, *Astronautics and Aeronautics*, 1967, p. 341. Cronkite's troubles were noted in Hugo Young et al., *Journey to Tranquility* (New York, 1970), pp. 220-221.
 24. Arthur Rudolph interview, 14 Dec. 1973. See also Sharpe, "Saturn," von Braun copy with marginal notes, p. 13.
 25. *Astronautics and Aeronautics*, 1967, p. 341.
 26. Schneider, teletype, 9 Nov. 1967; remark to reporters, "Apollo 4," p. 7.
 27. MSFC, *Saturn V News Reference*, 12.1-12.2. Each Saturn V flight was preceded by a technical summary including miscellaneous diagrams, mission profile details, and operational highlights. See, for example, MSFC, *Technical Information Summary, Apollo 4 (AS-501)*, and subsequent. A more comprehensive prelaunch publication, including details of the spacecraft and the launch facilities at KSC as well as the Saturn V launch vehicles, was issued as MSFC, *Saturn V Flight Manual, SA-501*, and subsequent. For a postmission analysis, see the continuing (and more voluminous) series of reports, such as MSFC, Saturn Flight Evaluation Working Group, *Saturn V Launch Vehicle Flight Evaluation Report AS-501, Apollo 4 Mission*, and subsequent. All of these documents may be consulted in the files of the MSFC Historical Off. In addition, see Lockyer, *A Summary of Major NASA Launchings* (cited for Saturn I and IB mission narratives), and MSFC, *Saturn V News Reference*, Dec. 1968. The annual issues of NASA, *Astronautics and Aeronautics* include pertinent summary information on the successive Apollo-Saturn launches and missions. An excellent survey of Apollo-Saturn vehicles and operations, covering AS-501/508, is David Baker, "Saturn V," *Spaceflight*, Jan., Feb., and Mar., 1971, pp. 16-22, 61-65, 100-107. Unless otherwise noted, information for the composite summaries of the Saturn V launches was compiled from the assorted documents noted above.
 28. For a clear and concise summary of vehicle AS-501 mission operations, see Haggerty, "Apollo 4," pp. 5-7; Baker, "Saturn V," *Spaceflight*, Mar. 1971, p. 100.
 29. Von Braun daily journal, transcript of telephone call 15 Nov. 1967, ASRC files.
 30. George Mueller to William M. Allen, 21 Nov. 1967.
 31. Gen. Phillips to NASA centers, teletype, 15 Nov. 1967.
 32. For the most concise assessment of the POGO investigation and ASI line analysis, see von Braun, "The Detective Story Behind Our First Manned Saturn V Shot," *Popular Science*, 193 (Nov. 1968): 98-100, 209. The quotations by von Braun have been taken from this source. On the background of the POGO problem and detailed study of the phenomenon, see L. L. Bickford and S. G. Meisenholder, *POGO Analysis of the Saturn Propulsion System (Final Report)*, NASA CR-86432, 3 Apr. 1967; George L. von Pragenu, "Stability Analysis of Apollo-Saturn V Propulsion and Structure Feedback Loop," AIAA Paper 69-877, Aug. 1969. See also interviews with von Braun, MSFC, 30 Nov. 1971; Roy Godfrey, MSFC, 29 July 1975; and Robert Pease,

NOTES TO PAGES 364-377

- MSFC, 3 Sept. 1971. The ASI line failure in particular is analyzed in Beirne Lay, Jr., *Earthbound Astronauts* (Englewood Cliffs, New Jersey, 1970), pp. 142-146.
33. Anon., "Manned Space Flight Program Progress," draft, 8 June 1967.
 34. Robert O. Aller to Dir., Apollo Program, 9 June 1967.
 35. Gilruth to George E. Mueller, 19 Sept. 1967.
 36. Von Braun daily journal, von Braun and Mueller teleconference, 11 Apr. 1968, ASRC files.
 37. NASA, *Astronautics and Aeronautics, 1968*, pp. 92-93; Arthur Rudolph to Gen. Phillips, telegram, 29 Apr. 1968.
 38. Arthur Rudolph to Gen. Phillips, "Replacement of F-1 engine on AS-503," 14 May 1968, and attachment, William D. Brown, Mgr., Engine Program Off. to Arthur Rudolph, "Leaking F-1 Primary Fuel Pump Seal on Engine F-4023, AS-503," 13 May 1968.
 39. Phillips' recollections are recounted in his essay, "The Shakedown Cruises," in Edgar M. Cortright, ed., *Apollo Expeditions to the Moon*, NASA SP-350 (Washington, 1975), pp. 171-175. All quotations are from this source. See also Brooks, Grimwood, and Swenson, *Chariots for Apollo*, chap. 12; Frank W. Anderson, Jr., *Orders of Magnitude: A History of NACA and NASA, 1915-1976*, NASA SP-4403 (Washington, 1976), p. 69.
 40. Mueller to Acting Administrator, "Request for Approval to Man the Apollo/Saturn V Launch Vehicle," 5 Nov. 1968; Mueller to Dr. Thomas O. Paine, 11 Nov. 1968, with attachments; Phillips to Mueller, "Apollo 8 Mission Selection," 11 Nov. 1968; Paine to Mueller, 18 Nov. 1968.
 41. Dieter Grau interview, MSFC, 24 Aug. 1971.
 42. NASA, *Astronautics and Aeronautics, 1968*, pp. 318-320; Lockyer, *Summary of Major NASA Launchings*, p. 128. Copy of Apollo 8 invitation housed in JSC files.
 43. Lockyer, *Summary of Major NASA Launchings*, pp. 127, 129; NASA, *Astronautics and Aeronautics, 1969*, pp. 62-65, 142-145.
 44. Michael Collins, *Carrying the Fire: An Astronaut's Journeys* (New York, 1974), pp. 358-359.
 45. NASA, *Astronautics and Aeronautics, 1969*, pp. 209-210.
 46. Michael Collins interview, 17 Oct. 1975; Collins, *Carrying the Fire*, pp. 364-365.
 47. Collins interview; Collins, *Carrying the Fire*, pp. 371-373.
 48. Collins, *Carrying the Fire*, pp. 371-373.
 49. The most convenient summary of the AS-506 mission is contained in NASA, *Astronautics and Aeronautics, 1969*, pp. 212 ff. It includes a wide range of editorial and public comment on the flight of *Apollo 11*, its significance and results. For published accounts see, for example, Neil Armstrong, Michael Collins, and Edwin Aldrin, *First on the Moon* (New York, 1970); Young, and others, *Journey to Tranquility*; Collins, *Carrying the Fire*; Norman Mailer, *Of a Fire on the Moon* (Boston, Massachusetts, 1969). See also Brooks, Grimwood, and Swenson, *Chariots for Apollo*.
 50. See, for example, Boeing Co., "Saturn V Flight Evaluation Trend Report: AS-501 Through AS-506," 30 Sept. 1969.
 51. NASA, *Astronautics and Aeronautics, 1969*, pp. 372-374; "Towards the Ocean of Storms," *Time*, 21 Nov. 1969, p. 8.
 52. Von Braun interview, MSFC, 17 Nov. 1976; Roy Godfrey interview, MSFC, 29 July 1975; Walter Haeussermann, MSFC, to author, "History of Saturn Launch Vehicles," 22 June 1976.
 53. NASA, *Astronautics and Aeronautics, 1970*, pp. 119 ff., 201 ff. See also, Edgar M. Cortright, "Report of the Apollo 13 Review Board," 15 June 1970. The report includes a one-volume narrative summary, and three volumes of appendices. Copies in JSC files. See also Brooks, Grimwood, and Swenson, *Chariots for Apollo*.
 54. NASA, *Astronautics and Aeronautics, 1971*, pp. 25 ff.; MSFC, Public Affairs Off., news release, 5 Feb. 1971.
 55. Commentary on the LRV can be found in David S. Akens, *An Illustrated Chronology of the NASA Marshall Center and MSFC Programs, 1960-1973*, MSFC, MHR-10, May 1974. On manned exploration of the lunar surface, including use of the LRV, see Richard S. Lewis, *The Voyages of Apollo: The Exploration of the Moon* (New York, 1974).
 56. Interviews with von Braun, MSFC, 30 Nov. 1971; Richard N. Rodgers, MSFC, 24 Aug. 1971; Leonard Bostwick and Milan Burns, MSFC, 31 July 1975. See also Jonathan Eberhart, "Saturn V Only a Beginning," *Science News*, 11 Nov. 1967, pp. 472-473.

NOTES TO PAGES 378–390

57. For a review of the scientific gear, experiments, and results, see Richard S. Lewis, *The Voyages of Apollo: The Exploration of The Moon* (New York, 1974).

CHAPTER 13

1. David S. Akens, *Skylab Illustrated Chronology, 1962–1973*, MSFC, 1 May 1973, pp. 1–7; James T. Murphy to Robert G. Sheppard, "Comment Edition of History of Saturn Launch Vehicles," with enclosures, 15 June 1976.
2. Akens, *Skylab*, pp. 32–34.
3. Akens, *Skylab*, pp. 41–43; David S. Akens, *An Illustrated Chronology of the NASA Marshall Center and MSFC Programs, 1960–1973*, MSFC, MHR-10, May 1974, pp. 328, 332.
4. Akens, *Skylab*, pp. 55, 70–71.
5. Akens, *Chronology of MSFC*, pp. 333–341. For the full story of Skylab, see Charles D. Benson and W. David Compton, *Skylab: A History*, the forthcoming official NASA history.
6. For details of the ASTP launch and background, see NASA, *Apollo-Soyuz Test Project: Press Kit* (1975). Copy in JSC files.
7. The most authoritative single volume on Soviet launch vehicles and other Soviet space technology is Senate Committee on Aeronautical and Space Sciences, *Soviet Space Programs, 1966–1970*, staff report, 92nd Cong., 1st sess., 9 Dec. 1971. This document includes a general discussion of the standard launch vehicle series, known as the A version, p. 135 ff. The discussion is preceded by a highly useful table of the characteristics of Soviet launch vehicles, on pp. 133–134. Illustrations are included on pp. 560–561, 563, 572–573. See also, Peter L. Smolders, *Soviets in Space* (New York: Taplinger Publishing Co., 1974). This book is translated from the Dutch edition which appeared in 1971. The author used no footnotes, but apparently he had access to an unusually large amount of unpublished information, and had opportunities for interviews with a number of leading Russian cosmonauts and scientists. A good, brief discussion of Soviet rockets appears on pp. 59–69, a useful illustration on p. 64, and a numbered, cut-away diagram of the Salyut vehicle on pp. 70–71. A recent survey of rocket technology, including the Russian vehicles, is Kenneth Gatland, *Missiles and Rockets* (New York: Macmillan Co., 1975), pp. 184–199 especially. This discussion includes comments on some of the later engines and on the range of Soviet rockets, as well as photographs of the engines themselves. Useful and detailed illustrations, done by a professional illustrator team, appear on pp. 76–82. These include a very useful illustration of the RD-107 engine (p. 77) as well as a launch profile of a Soyuz mission (p. 81). A noted expert and writer on space technology, Gatland is editor of the authoritative British magazine, *Spaceflight*. See also Nicholas Daniloff, *The Kremlin and the Cosmos* (New York: Alfred A. Knopf, 1972); and Leonid Vladimirov, *The Russian Space Bluff* (New York: Dial Press, 1973). The latter was written by a former mechanical engineer and scientific editor from the Soviet Union, who decided to defect in 1966. His intriguing thesis is that the Russians remained one step ahead of the U.S. during the 1960s because they felt that American space programs were further ahead than they actually were, and the Russians undertook a series of very risky space shots to maintain their propaganda advantage. The publisher included a comment by von Braun that the book was "fascinating, informative and worthy of a wide readership in the United States" (cited opposite the book's title page).
8. See Vladimirov, *Russian Space Bluff*, pp. 79–80. The comment on the heavy gauge of Soviet tankage is from U.S. Senate, *Soviet Space Programs*, p. 136.
9. Gatland, *Missiles and Rockets*, pp. 192–199. For a brief discussion of Russian propellant development, see John D. Clark, *Ignition! An Informal History of Liquid Rocket Propellants* (New Brunswick, N.J., 1972), pp. 115–119.
10. MSFC, press release, 5 Aug. 1975. For the full story of ASTP, see Edward and Linda Ezell, *The Partnership: A History of the Apollo Soyuz Test Project*, NASA SP-4209 (Washington, 1978).
11. See, for example, Loyd S. Swenson, Jr., "The Fertile Crescent: The South's Role in the National Space Program," *Southwestern Historical Quarterly*, 71 (Jan. 1968): 377–392. Obviously, the impact of NASA's presence varied. MSC was sited near an existing metropolis (Houston) of considerable size. KSC, in Brevard County, Fla., was located in an area of several smaller communities. MSFC, near Huntsville, was established near a medium-sized, though well-

NOTES TO PAGES 391-400

- established, city. MAF occupied existing facilities within the New Orleans metropolitan area, whereas MTF was largely a huge buffer zone for testing, different in concept from all of the above, employing a smaller number of permanent civil service and contractor personnel. Thus, the subtleties of NASA impact were different in each case, despite general patterns in terms of jobs, construction, and so on. See also Raymond A. Bauer, *Second-Order Consequences: A Methodological Essay on the Impact of Technology* (Cambridge, Mass.: MIT Press, 1969). Huntsville and Brevard County are specifically contrasted on pp. 92-101.
12. John S. Beltz, "Huntsville and the Aerospace Age," paper presented at the annual meeting of the Southern Historical Assn., Houston, 1971. Copy in SHP files. The Huntsville *Times*, "25 Years Since," 3 Nov. 1974. This was a special 16-page supplement to the *Times*, commemorating the 25th anniversary of the decision to locate the Redstone Arsenal in Huntsville in 1949. The supplement included numerous signed articles on various phases of the impact on Huntsville in the ensuing two and one-half decades. Cited hereafter as *Times*, Supplement.
 13. Bob Ward, "Famed von Braun Remembers Huntsville His Personal Choice," *Times*, Supplement, p. 4.
 14. Bauer, *Second Order Consequences*, p. 93; Beltz, "Huntsville," pp. 18-21.
 15. Beltz, "Huntsville," 21-22. Don Eddins, "City Schools," p. 11, John Park, "Medical Help Boomed," p. 15, in *Times*, Supplement.
 16. Don Eddins, "University of Alabama Spreads Wings," *Times*, Supplement, p. 13. The prior existence of a primarily Black state college, Alabama A&M, founded in 1873, seemed to underscore lingering racial divergences. Nevertheless, Huntsville's civil rights issues remained less volatile than elsewhere in the South during the turbulent 1960s. See Bauer, *Second-Order Consequences*, p. 98.
 17. Bob Ward, "Small Error Turned Out to Be More Fact Than Fiction," *Times*, Supplement, p. 2.
 18. *Times*, Supplement, *passim*.
 19. Alan Moore, "Von Braun Civic Center Heralds Future," *Times*, Supplement, p. 14; information supplied by the Alabama Space and Rocket Center.
 20. Bauer, *Second Order Consequences*, pp. 171-172, 174.
 21. For a popular account of these and other aspects of the national space program in general, see, Frederick I. Ordway III, Carsbie C. Adams, and Mitchell R. Sharpe, *Dividends from Space* (New York, 1971).
 22. Bauer, *Second Order Consequences*, p. 174.
 23. William R. Lucas, "The Past, Present, and Future of Metals for Liquid Rockets," *Metals Engineering Quarterly*, Feb. 1966, p. 59.
 24. R. V. Hoppes, "The Saturn V Space Program and Aluminum Welding Technology," MSFC, 1967, p. 10.
 25. Hoppes, "Saturn Welding Technology" p. 3, *passim*.
 26. *Ibid.*, pp. 5, 24-25.
 27. See, for example: "Listing of Special Publications Published by the NASA Technology Utilization Division," 1968; NASA, *Transferable Technology: Publications Reporting Innovations Suitable for Many Purposes*, NASA Off. of Technology Utilization, Fall 1968; House Committee on Science and Astronautics, "For the Benefit of All Mankind; a Survey of the Practical Returns from Space Investment," House report, 91st Cong., 2nd sess., 7 Dec. 1970; JSC, "Space Benefits: Today and Tomorrow," pamphlet, Nov. 1971.
 28. This became a standard interview question, even though it invariably elicited the same answer.
 29. Statements to this effect were made to the author by numerous contractors as well as MSFC managers and engineers, and printed in various press releases. See, for example, MSFC, Press Release 75-174, 1975.

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Sources and Research Materials

DOCUMENTARY SOURCES

This history rests primarily on documents acquired for the Saturn history project, under a contract awarded to the University of Alabama in Huntsville by MSFC in 1968. Documents in the Saturn history project (SHP) amount to approximately 24 file drawers and are currently housed in the library of the University of Alabama in Huntsville. Although the SHP files contain letters, memoranda, and other documents copied from the History Office at NASA Headquarters, as well as some material from the Kennedy and Johnson Presidential Libraries, their principal strength is represented in other aspects. The SHP files are primarily a collection of MSFC documents and materials gathered from contractors involved in the Saturn program. These documents include many unpublished reports and summaries prepared for miscellaneous briefings and professional meetings. Where no official control number was included, the source has been identified as NASA Report, Douglas Report, etc.

Many engineers who were involved in the Saturn program read papers at professional meetings of the American Institute of Aeronautics and Astronautics, and many were reprinted and cited herein as AIAA Paper No. 0000, etc. These AIAA papers were very valuable in coming to grips with many key areas in Saturn development, in discussing problems encountered, in trouble-shooting, and in assessing the solutions adopted. For the most part, these papers are notably candid and, because their authors were directly associated with Saturn hardware, can be regarded as useful primary sources. The SHP files also include selected correspondence, test reports, flight summaries, press kits, and other miscellaneous documents from NASA and contractor sources.

Although the files themselves are arranged in chronological order, there is an extensive and detailed index arranged by subject. The index is fully cross-referenced and annotated. Additional documents, acquired

STAGES TO SATURN

during later phases of the Saturn history, are housed with the SHP files, although they still await indexing and location within the original files.

Finally, the SHP files include tapes, transcripts, and notes of 128 interviews with NASA and contractor personnel who worked on the Saturn rockets. Unhappily, some of the interviews were recorded on tapes of inferior quality and the transcriptions are only marginal or fragmentary. A number of other transcriptions, although prepared from audible tapes, were so poorly transcribed as to be unusable. Notes were taken of several interviews when use of recording equipment was either impractical or impossible. Other interviews, housed in the files of Johnson Space Center or at NASA Headquarters in Washington, D.C., are so identified in the backnotes.

In identifying authorship or affiliation with government agencies and contractors, the following abbreviations have been used:

NASA	(National Aeronautics and Space Administration)
MSFC	(Marshall Space Flight Center)
KSC	(Kennedy Space Center)
JSC	(Johnson Space Center)
MDAC	(McDonnell Douglas Astronautics Company)
NAR	(North American Rockwell)

In citing interviews, these abbreviations have also been used to indicate the affiliation of the person who gave the interview. "NASA" in the interviews identifies individuals primarily associated with NASA Headquarters in Washington. Although von Braun was interviewed while he was attached to NASA Headquarters (as Deputy Associate Administrator for Planning) following his departure from MSFC in March 1970, I have identified him as an affiliate of MSFC because of his close association with Marshall and the Saturn program.

Several other documentary sources were used in writing the Saturn history. The files of the Historical Office, Marshall Space Flight Center, although including miscellaneous correspondence, were strongest in the series of monthly, quarterly, and annual progress reports of major laboratories and individual MSFC programs. These files were especially useful in establishing chronological sequences and specific dates. Other files consulted are now in MSFC's Records Holding Area. These include the Director's Reading Files (1960–1969); Office of the Director, "Weekly Notes" (1960–1968); Industrial Operations, Director's Reading Files (1960–1970); Industrial Operations, Record Files (1960–1970). I was unable, apparently because of internal bureaucratic inertia, to gain access to these files until a late phase of research. Fortunately, I do not seem to have missed much. The files were disappointingly thin in any matter of substance and dealt mostly with day-to-day managerial and budgetary

SOURCES AND RESEARCH MATERIALS

issues. The "Weekly Notes" were an exception, including several folders on special projects, as well as the weekly summaries from program managers and lab chiefs to von Braun, all with his rejoinders, queries, and directions scribbled in the margins.

Aside from the SHP files, the most rewarding source of correspondence and memos came from the historical files at NASA Headquarters, and from the files at Johnson Space Center. The latter included a wide range of direct correspondence among Headquarters, MSFC, and JSC. Because much correspondence from NASA Headquarters to JSC included information relevant to the Apollo-Saturn program as it involved other centers, the JSC files contained a remarkable amount of material pertinent to the Saturn.

The historian who delves into any of these files and expects to find signed, original documents is going to be disappointed. They must exist somewhere, but I did not see them. Apollo-Saturn not only flourished in the "age of the copier," it was one of its chief customers. For all practical purposes, there is nothing wrong with a copy, but the inability to find and actually handle the original takes some of the zest from historical research. The telephone is another obvious stumbling block in modern research. NASA and contractor personnel alike emphasized their reliance on the telephone to resolve problems and formulate policy on an ad hoc basis, making many decisions nearly impossible to trace. For this reason, interviews were often the only way to reconstruct some events. Wherever possible, data and controversial issues discussed in interviews were double checked against extant documentation, and/or in subsequent interviews with other people. Von Braun, however, kept a "Daily Journal," that listed hourly appointments, travel itineraries, and phone calls. Sometimes the Daily Journal included summaries of conversations, and sometimes it included verbatim transcriptions. In several instances, this made the "Daily Journal" an invaluable aid in understanding an event. The "Daily Journal" frequently included copies of memos and other instructions.

The SHP files and other documentary files used during preparation of the manuscript are listed below. (Although the manuscript includes material available in the files of the History Office, NASA Headquarters, it is not listed here because copies were made and housed in the SHP and JSC files.)

SHP files	Saturn History Project, Marshall Space Flight Center
MSFC files	Files of the History Office, Marshall Space Flight Center
MSFC/RHA files	Files in the MSFC Records Holding Area
JSC files	Files of the History Office, Johnson Space Center

STAGES TO SATURN

- | | |
|------------|---|
| SPO files | Files of the Saturn V Program Office, Marshall Space Flight Center |
| ASRC files | Files of the Alabama Space and Rocket Center, Huntsville, Alabama. Wernher von Braun's Daily Journal is housed in the ASRC files. |

Unless otherwise noted, all correspondence, memos, government documents, contractor reports, miscellaneous papers, and taped interviews are housed in the SHP files.

OTHER SOURCES

The manuscript's bibliography is represented in its backnotes. These notes frequently include annotations on the direct citation, in addition to a brief discussion of other relevant sources. Because of the extent and nature of modern governmental documentation, this short bibliographical essay describes classes of documents in place of an extensive and formal listing of sources. It is a summary of selected sources already discussed within the backnotes themselves. The titles that follow are those that the author most frequently consulted as a starting point, or for guidelines, enlightenment, and specifics, particularly as they pertained to NASA and the Saturn programs.

REFERENCE AND BACKGROUND

A good bibliographic reference is Katherine Murphy Dickson, *History of Aeronautics and Astronautics: A Preliminary Bibliography* (Washington: NASA, 1968). Dickson's work is particularly valuable because of the succinct annotations. *Astronautics and Aeronautics: Chronology on Science, Technology, and Policy* (Washington, 1963—) is issued annually and contains reference sources for each entry. For a well-illustrated historical survey of rocketry, see Wernher von Braun and Frederick I. Ordway III, *History of Rocketry and Space Travel* (New York, 1969). With von Braun as co-author, the book carries special authority in its discussion of many phases of the von Braun team, ABMA, and the Saturn program. Eugene M. Emme, ed., *The History of Rocket Technology: Essays on Research, Development, and Utility* (Detroit, 1964), features essays by historians, as well as participants, including von Braun. Two other edited works, with contributions by key engineers and managers themselves, are of special value. Ernst Stuhlinger, Frederick I. Ordway III, Jerry C. McCall, and George C. Brown, eds., *Astronautical Engineering and Science. From Peenemuende to Planetary Space* (New York, 1963), includes a variety of semitechnical discussions, prepared by engineers, that provide a good feel for the state of astronautics in the early 1960s. The book was a *festschrift* honoring Wernher von Braun on his 50th birthday, and its contributors had been his associates at Peenemuende, Fort Bliss, and Huntsville. Most of the essays have a historical theme. Edgar M. Cortright, ed., *Apollo Expeditions*

SOURCES AND RESEARCH MATERIALS

to the Moon (Washington, 1975), is a superbly illustrated retrospective summary of the Apollo-Saturn program, written by NASA astronauts and executives. Von Braun authored the essay on the Saturn.

Several of NASA's historical monographs were especially useful in dealing with early space programs and with early NASA activities. These include Constance Green and Milton Lomask, *Vanguard: A History*, NASA SP-4202 (Washington, 1971); Robert L. Rosholt, *An Administrative History of NASA, 1958-1963*, NASA SP-4101 (Washington, 1966); and Loyd S. Swenson, James M. Grimwood, and Charles C. Alexander, *This New Ocean: A History of Project Mercury*, NASA SP-4201 (Washington, 1966). For numerous charts, tables, and graphs, on manpower, funding, and organization, see Jane Van Nimen, Leonard C. Bruno, and Robert L. Rosholt, *NASA Historical Data Book, 1958-1968*, vol. I, NASA Resources, NASA SP-4012 (Washington, 1976). Bruce Mazlish, ed., *The Railroad and the Space Program: An Exploration in Historical Analogy* (Cambridge, Mass., 1965), offered a helpful framework for historical perspectives.

The titles noted above were useful for Part One and throughout the Saturn history. For specific sections of the book, the following titles were especially valuable.

PART TWO

Through its history office, MSFC sponsored its own series of historical reviews. Volume I was published as *Historical Origins of the George C. Marshall Space Flight Center* (1960), designated as MHM-1. Subsequent titles, numbered sequentially, were called *History of the George C. Marshall Space Flight Center* and issued semiannually through MHM-11 (1965). Companion volumes (designated as "Volume II" for each title) reproduced key documents cited in these histories. Beginning in 1966, the semiannual histories became annual *Chronologies*, designated MHR-6 and subsequent, ending in 1969. Based largely on these publications, MSFC issued a convenient chronology, David S. Akens, *Saturn Illustrated Chronology: Saturn's First Eleven Years, April 1957 Through April 1968* (MSFC, 1971), which furnished appropriate dates and titles of relevant documents for further research.

PART THREE AND PART FOUR

These sections deal with the principal components of Saturn hardware. Heinz H. Koelle, ed., *Handbook of Astronautical Engineering* (New York, 1961), provides an excellent survey of astronautical state of the art as of the early 1960s. This encyclopedic book treats structures, propulsion, guidance, and other significant topics. See also, Frederick I. Ordway III, James Patrick Gardner, and Mitchell R. Sharpe, *Basic Astronautics* (Englewood Cliffs, N.J., 1962), an introductory text by authors especially oriented to NASA's launch vehicle program.

STAGES TO SATURN

Two invaluable references for understanding the Saturn launch vehicles themselves are NASA-MSFC, *Saturn IB News Reference* (1968), and NASA-MSFC, *Saturn V News Reference* (1968). Produced by MSFC in cooperation with the major Saturn contractors, each three-ring loose-leaf volume illustrates essential Saturn systems, subsystems, components, and miscellaneous hardware. The accompanying text describes, in semitechnical terms, the function and operation of a bewildering array of Saturn hardware. As a means of grasping the complexities of the Saturn launch vehicle and the essentials of the different stages, including tankage, engines, and guidance, they are indispensable.

On engines, in particular, see Dieter K. Huzel and David H. Huang, *Design of Liquid Propellant Rocket Engines*, NASA SP-125 (Washington, 1971). Both men were Rocketdyne engineers; although the book's numerous fine illustrations do not specifically identify engine components, the illustrations and descriptions obviously owe much to Rocketdyne's development and production of the H-1, F-1, and J-2, making this publication uniquely interesting for the Saturn history. William J. Brennan, a top Rocketdyne executive, presented to an AIAA meeting a succinct but comprehensive historical overview of rocket engines, "Milestones in Cryogenic Liquid Propellant Rocket Engines," published as AIAA Paper 67-978 (Oct. 1967). For the Saturn generally, see Leland F. Belew, W. H. Patterson, and J. W. Thomas, Jr., "Apollo Vehicle Propulsion Systems," AIAA Paper 65-303 (July 1965).

The procedures used in the fabrication of stages borrowed from prior aircraft experience and from extant techniques used in military rocket boosters. A useful semitechnical overview of contemporaneous practice is Frank W. Wilson and Walter R. Prange, eds., *Tooling for Aircraft and Missile Manufacture* (New York, 1964). Nevertheless, production of the various stages of Saturn presented new problems in metallurgy, tooling, and welding. The evolution of the S-IVB upper stage presented many typical problems. See, for example, K. H. Boucher, "Saturn Third Stage S-IVB Manufacturing," Douglas Paper 3707 (1965), and E. Harpoothian, "The Production of Large Tanks for Cryogenic Fuels," Douglas Paper 3155 (1964). For discussion of the S-IC, see George Alexander, "Boeing Faces Unique Fabrication Challenge," *Aviation Week and Space Technology*, 77 (13 Aug. 1962): 52-63; Whitney G. Smith, "Fabricating the Saturn S-IC Booster," AIAA Paper 65-294 (1965). The S-II stage was plagued by welding problems, as described in an anonymous article, "The Toughest Weld of All," *Skyline* (1968), an unpagged reprint in the SHP files. Despite an obvious bias, company magazines like North American's *Skyline* and Boeing's *Boeing Magazine* frequently carried valuable descriptive articles and illustrations. The authoritative articles in *Aviation Week and Space Technology* are also valuable for their depth and accuracy.

On computers and guidance, see D. Morris Schmidt, "Survey of

SOURCES AND RESEARCH MATERIALS

Automatic Checkout Systems for Saturn V Stages," MSFC, 10 July 1968. C. Stark Draper, Walter Wrigley, and John Hovorka, *Inertial Guidance* (New York, 1960), is a basic treatise. A study closely related to the Saturn program and its immediate predecessors is F. K. Mueller, "A History of Inertial Guidance," ABMA, Redstone Arsenal, Ala. (1959), written by one of the originators of the guidance systems for the V-2.

PART FIVE

For a comprehensive analysis of management theories and organization at the height of the Apollo-Saturn program, see Apollo Program Office, NASA Headquarters, *NASA-Apollo Program Management* (1967), a project that covered NASA centers as well as major contractors, and ran to 14 volumes. For all this elaborate managerial superstructure, the flavor of operational problems and frustrations stands out in annual reviews like NASA Headquarters, Office of Programs and Special Reports, *Program Review: Apollo* (1962–1966). The complexities of logistics near the peak of Apollo-Saturn can be examined in *First Annual Logistics Management Symposium, 13–14 September 1966*, NASA TMX-53566 (16 Jan. 1967). See also John C. Goodrum and S. M. Smolensky, "The Saturn Vehicle Logistics Support System," AIAA Paper No. 65–268 (April 1965).

PART SIX

The best single summary reference for all Saturn I, Saturn IB, and Saturn V launches is the tabulation by William A. Lockyer, Jr., ed., *A Summary of Major NASA Launchings, Eastern Test Range and Western Test Range: October 1, 1958 to September 30, 1970*, Kennedy Space Center, Fla., Historical Report No. 1 (Revised, 1970). A readable and instructive account of launch activities at Cape Kennedy and the launch of a Saturn V is Gene Bylinsky, "Dr. von Braun's All-Purpose Space Machine," *Fortune*, 75 (May 1967): 142–49. For dimensions, weights, duration, and other specifics of Saturn V launches, see MSFC, *Saturn V Flight Manual*, SA-501, through SA-509, which was the last flight manual issued. Astronaut Michael Collins has written a marvelous, colorful memoir, *Carrying the Fire: An Astronaut's Journeys* (New York, 1974), that includes his account of what it was like to ride a Saturn V into space.

PART SEVEN

Raymond A. Bauer, *Second-Order Consequences: A Methodological Essay on the Impact of Technology* (Cambridge, 1969), is an insightful and

STAGES TO SATURN

provocative book generally concerned with the implications of space exploration. The local impact on Huntsville is graphically conveyed in the special supplement of the Huntsville *Times*, "25 Years Since" (3 Nov. 1974), in remembrance of the evolution of rocketry since the von Braun group's arrival at Redstone Arsenal in 1949.

Index

The appendixes are not included in the index.

- Acceptance Test or Launch Languages(ATOLL), 237, 256, 398
Actuator (flight control system), 182
Advanced Research Projects Agency (ARPA), 31, 39, 56, 133, 135; defense funding, 26–27, 29–30, 35, 76, 299; and NASA programs, 33, 34, 38; and Saturn program, 23, 37
Advanced Vehicle Team (LaRC), 61
Advent (communications satellite), 135
Aero Spacelines, Inc., 309–17
Aerobee (sounding rocket), 17
Aerojet General Engineering Corp., 60, 130–31, 210
Air Force, U.S., 13–14, 17, 25, 35, 37, 135, 137, 149; civilian space program, aid to, 19, 35, 36, 98, 111; contractor relations, 194–95, 288–89; F-1 engine program, 26, 105, 123, 127; liquid hydrogen research, 131, 135–36; Pregnant Guppy detention, 317–18; and Saturn program, 39–40, 43, 57
Air transport, 293, 302, 308–18
Airlock module (Skylab), 382
Alabama Space and Rocket Center, 394, 395 ill.
Aldrich, David E., 110
Aldrin, Edwin E., 3, 5, 6 ill., 363, 369, 371–72, 373 ill.
All-up concept, 347–49, 351, 356 ill., 357, 360, 377
Allen, William M., 360
Alloy, 194; aluminum, 101, 119, 165, 201, 203, 217, 396; beryllium 248, 250–51, 257, 398; magnesium-lithium, 250–51, 257, 397–98; nickel, 102, 119
Anders, William A., 367
Animals in space, 19, 327
Apollo Applications Program (AAP), 382
Apollo Applications Program Office, 382
Apollo Executive Group (contractors), 276
Apollo Program Office, 230, 254, 278, 285, 291, 295
Apollo Saturn (Apollo space vehicle and flight).
 See Apollo Saturn IB, Apollo Saturn V.
Apollo Saturn IB:
 AS-201, 148, 187, 253, 338–39, 340, 349
 AS-202, 339, 340, 341, 343
 AS-203, 339–40, 341, 349
 AS-204 (Apollo I), 340–41
 AS-204 (*Apollo 5*), 340–41, 343–44
 AS-205 (*Apollo 7*), 343 ill., 344, 345
 AS-206 (*Skylab 2*), 383–84
 AS-207 (*Skylab 3*), 383–84
 AS-208 (*Skylab 4*), 149, 383–84, 385 ill.
 AS-209 (ASTP; Skylab), 384, 389
 AS-210 (ASTP), 385
Apollo Saturn V:
 AS-501 (*Apollo 4*), 223, 228–32, 254, 321, 347–49, 351–55, 356 ill., 357–60, 364
 AS-502 (*Apollo 6*), 321, 364, 377
 AS-503 (*Apollo 8*), 321, 349, 363–68, 377, –78
 AS-504 (*Apollo 9*), 149, 364, 368
 AS-505 (*Apollo 10*), 368–69
 AS-506 (*Apollo 11*), 3, 321, 369–72, 378
 AS-507 (*Apollo 12*), 374–75
 AS-508 (*Apollo 13*), 375–76
 AS-509 (*Apollo 14*), 376
 AS-510 (*Apollo 15*), 376

STAGES TO SATURN

Apollo Saturn V, continued

AS-511 (*Apollo 16*), 376

AS-512 (*Apollo 17*), 376, 377 ill.

AS-513 (*Skylab 1*), 384

Apollo-Saturn program, 184, 285, 360, 370–71; booster-payload coordination, 61–62; 274; existing technology use, 21, 87, 131; growth, 267, 382; objectives, 261–62, 264, 381; problem prevention efforts, 103, 184, 262, 330, 374; success factors, 262, 264, 282, 288–89, 318, 337, 377, 397–99. *See also* All-up concept, Budget (NASA), Logistics program, Quality control, Technology transfer.

Apollo-Soyuz Test Project (ASTP), 127, 291, 379, 385, 386, 388, 389 ill., 401

Apollo spacecraft and missions:

Apollo 1 (AS-204), 340–41

Apollo 4 (AS-501), 340–41, 347–49, 351–60, 364

Apollo 5 (AS-204), 341, 343–44

Apollo 6 (AS-502), 344, 360

Apollo 7 (AS-205), 343 ill., 344, 345

Apollo 8 (AS-503), 321, 363–68, 378

Apollo 9 (AS-504), 364, 368

Apollo 10 (AS-505), 368

Apollo 11 (AS-506), 3, 4, 6 ill., 7, 125, 363, 369–72, 373 ill.

Apollo 12 (AS-507), 374–75

Apollo 13 (AS-508), 375–76

Apollo 14 (AS-509), 376

Apollo 15 (AS-510), 376

Apollo 16 (AS-511), 376

Apollo 17 (AS-512), 376, 377 ill.

Apollo telescope mount (ATM), 382–83

Appold, Norman C., 34, 45

Armstrong, Neil A., 3, 5, 6 ill., 363, 369, 371–72, 373 ill.

Army, U.S., 25, 35, 391; civilian space program, aid to, 19, 35–36, 298; liquid propulsion rocketry, 14, 131; missile development, 13–15; and Saturn program 39–40

Army Ballistic Missile Agency (ABMA), 15–16, 18, 25; booster programs, 25–30, 33–34, 298; civilian space program, aid to, 19–20, 33–40; and NASA program, 81, 157–58, 193; and Saturn program, 41–44, 69, 74, 76, 136, 243

Army Ordnance Missile Command (AOMC), 14, 30, 31, 42, 299

Arnold Engineering Development Center, 149, 390

Astrionics Laboratory (MSFC), 247, 328

Astronauts, 19, 20 ill., 383. *See also names of individual astronauts.*

Atlantic Missile Range, 16 ill.

Atlas (ICBM missile), 14, 17, 19, 20, 21, 34–36, 164, 189; liquid fuel use, 14, 44, 91; satellite payloads, 17, 134–35; and Saturn program, 37, 43, 120, 127, 141, 146

Atlas (launch vehicle), 17, 19, 20 ill., 21, 25, 44, 61 ill., 161, 134–35

Atlas-Agena, 61 ill.

Atlas-Centaur, 135

Atmospheric research, 17

ATOLL (Acceptance Test or Launch Languages), 237, 256, 398

Atomic Energy Commission (AEC), 13, 17

Atwood, J. Leland, 224, 226, 229, 231

Automation, 241; automated checkout, 186, 235–40; and welding, 218, 221 ill., 222

Auxiliary propulsion system (Saturn guidance and control system), 182, 256

B-377 (cargo aircraft), 309

B-377 PG. *See* Pregnant Guppy.

B-377 SG. *See* Super Guppy.

BARC amphibious vessel, 298

Balch, Jackson L., 74

Balsa wood insulation, 175

Barge, 298; *Compromise*, 305; *Little Lake*, 305;

Palaemon, 302–03, 304, 305, 306 ill., 307; *Pearl River*, 305, 306 ill.; *Poseidon*, 305, 306 ill., 307; *Promise*, 305, 307

Base heating phenomena, 78–79

Bauer, H. E., 167, 171, 189, 240, 302

Bauer, Raymond A., 394–96, 399

Baykonur Cosmodrome, 388

Bean, Alan L., 374

Belew, Leland F., 99, 148

Bendix Corp., 245, 248

Bergen, William B., 231

Bill Dyer (tugboat), 308

Bob Fuqua (tugboat), 303, 304, 307

Boeing Co., 116, 200, 352, 360; contracts, 105, 284; MSFC staff, work with, 192–96, 207, 239–40; NASA facilities use, 71, 73, 166, 194; production innovations, 201–03, 206

Booster. *See* Launch vehicle and Missile.

Borman, Frank, 367

Bostwick, Leonard C., 95–96, 104, 112

Bramlet, James B., 65, 193

Brand, Vance D., 389

Brennan, William J., 108, 113, 115

Budget (NASA), 54–55, 188, 297; logistics costs, 293, 295; long-range plans, 48, 50, 53. *See also* All-up concept.

Bumper (atmospheric research probe), 14

INDEX

- Camera capsules, 328, 338, 340
Canright, Richard B., 39, 134
Cape Canaveral, 14, 15, 70, 73, 80, 323. *See also* Cape Kennedy.
Cape Kennedy, 21, 101, 123, 125, 239, 317, 318, 332, 388–89
Cargo aircraft, 309–18
Cargo Lift Trailer (CLT), 315
Castenholz, Paul, 113
Centaur (launch vehicle upper stage), 36–38, 43; liquid hydrogen fuel, 44, 46, 51, 61 ill., 92, 131–35, 136 ill., 137; tank structure, 164, 167
Cernan, Eugene A., 368, 369
Chaffee, Roger B., 231, 340–41
Chance-Vought Corp., 82
Chrysler Corp., 15, 71–72, 81–83, 98, 102, 103, 196, 210, 331, 333, 385
Civilian space program, 41, 55
Cluster concept, 34, 35, 324; engine, 30, 36, 43, 51, 76, 79–80, 83, 97, 137, 160, 164, 334, 337, 345, 400; tank, 30, 43, 76, 77, 82 ill., 155
Collins, Michael, 3, 5, 363, 369–72
Combustion instability, 99, 101, 113–16, 398
Comet Kohoutek, 385
Command and service module (CSM), 5, 83, 161, 236, 247–48, 344, 359, 361, 363, 368, 369, 372; 384; Apollo 1 fire, 340–41; production delays, 226–27, 230–31
Committee for Evaluating the Feasibility of Space Rocketry (CEFSR), 130, 131
Compromise (barge), 305
Computer language, 236–37, 256, 398
Computer, 155, 235, 236 ill., 246 ill., 294–95; automated checkout, 236–41; guidance, 243, 249; innovations, 250–51, 398; PERT, 286–87
Conrad, Charles ("Pete"), Jr., 374, 384
Conroy, John M., 309–14
Contractor, 15, 96, 102, 268 ill., 281, 283, 360. *See also* Apollo Executive Group, Government-contractor relations, Management, Marshall Space Flight Center, Resident Manager's Office, and names of individual contractors.
Contract (NASA), 15, 42, 68, 284, 309; engine, 104–05, 137, 141, 143, 148; maintenance, 73–74; stage, 81, 157–59, 160, 210–11
Control Data Corp., 240
Convair Astronautics Div., General Dynamics Corp., 159, 173, 188, 210
Cook Technological Center, Cook Electric Co., 328
Cosmonaut, 19, 21, 54, 388. *See also* names of individual cosmonauts.
Crocco, Luigi, 114
Cronkite, Walter, 357
Cryogenics, 89, 90, 91, 94, 127, 130, 184, 198, 297, 398
Cummings Research Park, 395 ill.
Cunningham, R. Walter, 343

Dannenberg, Konrad, K., 263, 264
Davis, Wilbur, S., 211
Debus, Kurt H., 38 ill., 70, 231, 277 ill.
Defense, Dept. of, 15, 23, 282; booster program, 26, 36, 37; space program, 25, 27, 32, 55; and Saturn program, 38–42, 57, 297
Development Operations Div. (ABMA), 42
Direct ascent (Nova), 63, 65, 66, 83
Donn, William, 357
Doolittle, James H., 34
Dornberger, Walter R., 11, 12
Douglas Aircraft Corp., 169 ill., 182, 210, 240, 279 ill., 283, 309, 382; insulation innovations, 172–77; S-IV stage, 81, 136–37, 157, 158–59, 188–89, 331; S-IVB stage, 143, 147–48, 157, 160, 162, 168, 185–87, 278, 280; tank, 165–67, 170–72, 184–85
Draper, Dr. C. Stark, 242
Dryden, Dr. Hugh L., 32 ill., 34, 39, 40, 53, 55, 58, 67, 113
"Dry workshop." *See* Orbital Workshop.
Dyna-Soar, 35, 43, 47, 57, 58, 60

E-1 engine, 26, 27, 111
Earth orbit rendezvous (EOR), 59, 63, 65–67, 84, 162, 349, 400
Edwards Air Force Base, Calif., 68–69, 106, 107, 116, 123, 124, 126, 136
Eisenhower, Dwight D., 19, 27, 32 ill., 33, 41, 42, 43 ill., 50
Eisele, Donn F., 343
Electronics Communications Inc., 254
Engine Program Office (MFSC), 108, 140, 270
Explorer (satellite), 16 ill.
Explorer I, 18, 26, 70, 354
Explorer XVI, 330

F-1 engine, 26, 48, 51, 52, 87, 105, 110 ill., 122 ill., 142, 210, 302, 370, 397–98; innovations, 107–08, 119, 120–21, 127; problem phases, 95, 108–09, 112–14, 116, 153; Saturn V,

STAGES TO SATURN

- F-1 engine, continued
 C-5 configuration, 58–59, 65, 192–93;
 Saturn V, S-IC stage, 5, 106, 196, 198–99;
 207–08; 348, 352, 354, 357; testing program,
 106–07, 108, 111–12, 115, 117, 119, 123–
 26. *See also* Combustion instability, Fuel in-
 jector, Pogo effect, Thrust chamber, Turbo-
 pump.
- Fairchild Corp., 333
- Felix, Harold E., 185
- Flight Operations Office (GEM box), 274
- Ford Instrument Co., 243
- Frietag, Robert F., 313
- Friendship* 7, 20
- Fuel injector, 109–16, 138, 142, 145, 151 ill.
- Fuller, Paul N., 144
- Gagarin, Yuri A., 19, 54
- Gates, Thomas S., Jr., 41
- Gayle, J. B., 185
- Geissler, Ernst D., 38 ill., 59, 163
- GEM boxes, 270, 272 ill., 273, 289, 290, 292
- Gemini program, 21, 161, 294, 330, 336, 355,
 381
- General Accounting Office, 159
- General Dynamics/Astronautics, 132, 134–35,
 138
- General Electric Co., 14, 73–74
- Gilruth, Robert R., 61, 62, 63, 65, 229, 277 ill.,
 364, 373 ill.
- Glenn, John H., Jr., 20
- Glennan, T. Keith, 32 ill., 33, 38, 40, 41, 43,
 50, 51, 53, 57, 141, 159, 209
- Goddard, Robert H., 8–9, 10 ill., 91
- Goddard Space Flight Center (GSFC), 61
- Godfrey, Roy E., 162, 190
- Goett, Harry J., 41
- Golovin, Nicholas E., 63, 67, 351
- Goodrum, John C., 296, 307, 310, 311, 314,
 318
- Gordon, Richard F., 374
- Government-contractor relations, 15, 358, 397–
 400; MSFC contractor monitoring, 81, 98,
 102–03, 107, 113, 116, 124, 141, 184–85,
 193–95, 200–02, 213, 222–23, 226–27,
 230, 232, 257, 275, 277–78, 280–82, 292,
 296, 358, 361–62; NASA contractor manage-
 ment, 104, 159, 222, 224–32, 245–56, 274,
 288–89, 292
- Grace, Clinton, H., 245–46
- Grau, Dieter, 350, 366
- Greer, Robert E., 227, 228, 232
- Grissom, Virgil I., 231, 340, 341
- Grumman Aircraft Engineering Corp., 68
- Guggenheim Aeronautical Laboratory, Cali-
 fornia Institute of Technology, 10
- Guidance and control system, 7, 8, 52, 241,
 242, 247, 278, 250, 251
- Gyroscope, 242
- H-1 engine, 29, 39, 48, 87, 91, 94 ill., 100 ill.,
 105 ill., 120, 125, 127, 142, 153, 398; innova-
 tions, 99, 119; problem phases, 95, 101–04;
 Saturn I, 77, 97, 324, 325, 326, 328–29,
 336; Saturn IB, 83, 97, 338, 344; testing
 program, 98, 113, 115, 126. *See also* Combus-
 tion instability, Fuel injector, Teflon, Thrust
 chamber, Turbopump.
- Haeussermann, Walter, 38 ill., 350
- Haise, Fred W., Jr., 375
- Hall, Eldon W., 45, 47
- Hamilton, Julian S., 311
- Harrje, David, 114
- Haynes Stellite Co., div. of Union Carbide,
 103–04
- Heimburg, Karl L., 38
- Helicopter, 308, 316 ill.
- Helium, 177–78, 198, 199
- Hellebrand, Emil A., 183–84
- Hello, Bastian, 231
- Hermes C-1, 14
- Hermes program, 14
- High Altitude Test Vehicle (HATV), 130–31
- Highwater, Project, 325, 336, 345
- Hjornevik, Wesley L., 35, 36, 40, 41
- Hoelzer, Helmut, 38 ill.
- Hoffman, Samuel K., 34
- Holaday, William M., 27
- Holmes, D. Brainerd, 63, 65, 67, 114, 160,
 192, 211, 312, 349, 359–60
- Hoppes, R. B., 396
- Horner, Richard E., 45, 47, 50
- Hornig, Donald F., 113
- Houbolt, John C., 63, 64 ill.
- House Committee on Science and Astronautics,
 159
- Huetter, Hans, 38 ill.
- Huntsville, Ala., 379, 390–94
- Hyatt, Abraham, 34, 36, 41, 45, 158
- International Business Machines Corp. (IBM),
 240, 245, 246 ill., 247, 252–53, 386
- Industrial Operations Div., (IO, MSFC), 182,
 269–70, 286, 290
- Inertial guidance systems, 242, 243

INDEX

- Injector, *See* Fuel injector.
- Instrument unit (IU), 161, 241–57, 315, 386; automated checkout, 239–40; production procedures, 242–54; Saturn I, 244–45, 249; Saturn IB, 245, 246 ill., 247, 344; Saturn V, 241–42, 246 ill., 247–50, 255–56, 358–59, 360–61
- Insulation, 149, 172–77, 212, 213–15, 222–23, 358
- Intercontinental ballistic missiles (ICBM), 13, 91, 386, 400–01. *See also* Atlas, Minuteman, and Titan.
- Intermediate range ballistic missiles (IRBM), 16–91. *See also* Jupiter and Thor.
- International Geophysical Year (1957–1958), 17
- Invar piping, 152–53
- IU-204 (instrument unit), 254
- IU-205, 254
- IU-503, 254
- J-2 engine, 5, 58–59, 144, 151 ill., 187 ill., 240; failure, 360–63; liquid hydrogen technology, 127, 141, 143, 146–47, 359; problem phases, 144–45, 149–53, 372–73; S-II stage, 177, 210, 212, 216, 240, 348, 357; S-IVB stage, 160, 164, 171, 177–78, 180–82, 186, 256; Saturn IB, 87, 143, 338–40, 343–45, Saturn V, 143, 368, 371; testing program, 142–43, 147–49, 216. *See also* Fuel injector, Pogo effect
- JATO project (Jet-Assisted Take-Off), 10
- James, Lee B., 278–79, 280, 289, 399
- Jet Propulsion Laboratory, California Institute of Technology, 18, 33, 130, 132
- Johnson, Lyndon B., 31, 53, 54, 68 ill., 348, 369
- Johnson, Roy W., 27, 31, 33, 38, 40, 44
- Johnston, Herrick L., 131, 133, 147
- Jones, Robert E., 390
- Juno (launch vehicle), 18, 34
- Juno II, 25, 36
- Juno III, 27
- Juno IV, 27
- Juno V, 27–28, 31, 35, 36, 74, 76, 79, 191
- Juno V-A, 37
- Juno V-B, 37
- Jupiter (IRBM missile), 14, 15, 16, 30, 35, 70, 77, 83, 91, 95, 99, 127, 195, 244, 350
- Jupiter C (launch vehicle), 16 ill., 17, 18, 36
- Kennedy, John F., 53–56, 67, 68 ill., 348
- Kennedy Space Center (KSC), 3, 4, 6 ill., 184, 236 ill., 239, 332, 349, 351, 356 ill., 386, 390
- Kerosene-based propellant, 5, 89, 99, 102, 105, 127, 129, 232, 386, 387
- Kerwin, Joseph P., 384
- Killian, James R., 27, 31
- Killian committee, 27, 31
- Klute, Dan, 113
- Kroeger, Herman W., 311
- Kubasov, Valery, N., 388
- Kuers, Werner R., 219, 392
- Lambert, H. L., 301
- Land transport, 298–99, 300, 301, 318
- Lange, Oswald H., 136, 210, 211, 275
- Langley Research Center (LaRC), 44, 61–63
- Launch Complex 34, 70, 338, 343 ill.
- Launch Complex 37, 332, 334–35, 341
- Launch Complex 39, 4, 6 ill., 11 ill., 223, 347, 356 ill., 365 ill., 385 ill.; pad A, 383; pad B, 383
- Launch Operations Center (LOC), 70
- Launch Operations Directorate (LOD), 70
- Launch vehicle, 3–4, 17–21, 25–29, 33–41, 51–53, 56, 74. *See also* names of individual vehicles.
- Launch window, 293, 367
- Leonov, Aleksey A., 21, 388
- LEV-3 (inertial guidance system), 242–43
- Lewis Propulsion Laboratory, 44
- Lewis Research Center (LeRC), 44, 79, 84 ill., 132–134, 136–138, 145, 153, 173
- Liquid hydrogen, 8, 53, 127, 129–30, 184–85, 297; Centaur, used in, 36–37, 131, 133–35; J-2, used in, 127, 141, 144–45, 149–50, 177–82, 339–40, 345, 361; Lewis Laboratory research, 44, 132–33; RL-10, used in, 127, 137, 140, 144, 334; Saturn design, effect on, 44–47, 51, 58, 89, 134, 400; tanks, effect on, 147, 163–64, 167, 172, 174–78, 180, 192, 211–12
- Liquid oxygen (LOX), 5, 8, 12, 132, 151 ill.; multistage rockets, used in, 44, 45, 85, 162, 177, 386; liquid hydrogen, used with, 44, 51, 145, 147, 162; tanks, effect on, 77, 144, 149, 164, 167, 177–78, 181, 185, 198–99, 200, 202, 211, 213
- Little Lake (barge), 305
- Lockheed Aircraft Corp., 210
- Logistics Management Office (NASA Hq.), 296
- Logistics program, 292–96, 300–01, 318, 319, 398

STAGES TO SATURN

- Lovell, James A., Jr., 367, 375
Low, George M., 63, 226, 365–66, 373 ill.
LOX. *See* Liquid oxygen.
LR-115 engine, 137
LR-119 engine, 137, 160
LSD (Navy Landing Ship, Dock), 305, 319 ill.
Lubricant, 147
Lucas, William R., Jr., 185, 396
Lunar excursion module (LEM), 5, 68, 83, 193
Lunar module (LM), 161, 163, 236, 341, 343,
 344, 345, 368–69, 372
Lunar orbit rendezvous (LOR), 59–61, 63, 64
 ill., 65–68, 83, 84, 161, 162, 349, 367, 400
Lunar roving vehicle, 376, 377 ill.
- M-1 engine, 60
McDonnell Douglas Corp., 383, 386
McDivitt, James A., 368
McElroy, Neil H., 27
McKinsey and Co., 42
McNamara, Joseph P., 107
McNamara, Robert S., 68 ill.
Management, 261, 263–65, 272 ill., 290; NASA
 Hq–center relations, 257, 265, 270–271,
 274–75; von Braun policies, 261, 263–65,
 289, 291. *See also* GEM boxes, Government-
 contractor relations, Reorganization, Schedule
 delay.
Manned earth orbital missions, 54, 160, 363,
 364
Manned Flight Awareness Office, 279 ill., 283
Manned lunar landing, 7, 34, 36, 41, 48–49,
 50, 52, 56, 57, 59, 65, 66, 83, 105, 161,
 267, 336, 344, 357, 360, 364, 372, 381
Manned Spacecraft Center (MSC), 62, 63, 65,
 66, 70, 231, 313, 349, 390
Manned spaceflight, 7, 9, 19, 21, 32, 33, 51,
 141, 349, 367
Mariner mission, 137
Marshall, Mrs. George C., 42, 43 ill.
Marshall Space Flight Center (MSFC), 23, 42,
 43 ill., 59, 71 ill., 210, 246 ill., 261, 302,
 305, 310, 379, 396, 399, 400; NASA Hq,
 relations with, 160, 257, 266, 269–70; in-
 house capabilities, 70–71, 74, 81, 85, 124,
 136–37, 144, 192–93, 333; production fac-
 ilities, relations with, 68–73; research centers,
 relations with, 61–67, 79, 267, 390; Skylab
 program, 379, 382–83; testing program, 144,
 148–49, 184, 188, 337, 349, 367. *See also*
 Government-contractor relations, Resident
 Manager's Office.
- Mathews, Charles W., 373 ill.
Mattingly, Thomas K., II, 375
Maus, Hans H., 38 ill., 65, 193
Mechling Barge Lines, Inc., 303, 304
Medaris, John B., 15, 31, 34
Mercury, Project, 19, 21, 61, 161, 294, 355
Meteoroids, 329, 330, 331, 334
Michoud Assembly Facility (MAF), 68, 71–73,
 75 ill., 84 ill., 208 ill., 301, 383, 385, 390;
 Boeing, used by, 166, 192, 194, 195, 196,
 201–03, 206; Chrysler, used by, 81–82
Military rocketry, 9–16, 25, 31–32, 35, 39,
 40, 41, 53, 137
Minuteman (ICBM missile), 349, 351
Missile, 9–17, 21, 25, 54, 161. *See also* names of
 individual missiles.
Mississippi Test Facility (MTF), 68, 72–74, 75
 ill., 125, 144, 207, 208 ill., 221 ill., 229,
 301, 306 ill., 390; F-1 testing, 125, 206–
 07, 363; J-2 testing, 216, 224, 363
Moog Industries, 182
Mrazek, William A., 29, 30, 31, 38 ill., 43,
 45, 46, 65, 193, 307
Mueller, Fritz, 243
Mueller, George E., 226, 228–29, 276, 277 ill.,
 289, 334, 341, 360, 364, 366, 373 ill., 382;
 all-up concept, 348–51; GEM boxes, 270–71
Murphy, James T., 271
Muse, Thomas C., 45
Myers, Dale D., 225
- National Advisory Committee for Aeronautics
 (NACA), 19, 31–34, 68, 132, 134
National Aeronautics and Space Act of 1958,
 19, 32, 39, 54, 294
National Aeronautics and Space Administration
 (NASA), 21, 32, 258 ill., 383, 398–400;
 booster program, 33–36, 39–43, 58–60;
 liquid hydrogen program, 44–47; NACA,
 created from, 18–19, 31–34; planning, 48,
 50–53, 55, 57, 265. *See also* Army Ballistic
 Missile Agency, Apollo-Saturn Program,
 Budget (NASA), Contracts (NASA), Govern-
 ment-contractor relations, Manned lunar
 landing, Reorganization, Saturn program, and
 names of individual program offices.
Navaho (cruise missile), 13–14, 15, 16 ill.
Navaho project, 13–14, 15
Navy, U.S., 13, 15, 16, 17, 25, 27, 35, 130, 131,
 211, 305
Nelson, Richard H., 194
Neubert, Erich W., 38 ill.

INDEX

- Noise, 80, 357
North American Aviation, Inc. (North American Rockwell Corp. from Sept. 1967), 73, 146, 283, 371; contracts, 209–11, management problems, 225–32; production facilities, 166, 195, 212; production innovations, 213–15; production problems, 215, 217, 222, 230–33, 352
Nova (launch vehicle), 37, 39, 50–53, 57, 58, 59, 60, 63, 65, 66, 67
Nozzles, 92–93, 121–22
- Oberth, Hermann, 8, 9, 10 ill.
O'Connor, Edmund F., 188, 224, 225, 231, 254, 269, 289, 292, 295
Odishaw, Hugh, 58, 113
Office of Launch Vehicle Programs (NASA Hq.), 47
Office of Manned Space Flight (NASA Hq.), 63, 66, 113, 230, 275–76, 296, 366
Office of Program Planning and Evaluation (NASA Hq.), 51
Office of Space Sciences (NASA Hq.), 325
Orbital Workshop (Skylab), 126–27, 382, 383, 385 ill.
Ordnance Guided Missile Center, 15
Ostrander, Donald R., 48, 209
Oxidizers, 89, 91, 127, 149, 198–99
- Paine, Thomas O., 366, 373 ill., 383
Palaemon (barge), 302–05, 306 ill., 307
Pall Corp., 138
Panama Canal, 309
Parker, William F.: 228
Pearl River (barge), 305, 306 ill.
Pease, Robert E., 145, 150
Peenemuende, 11, 12, 291
Pegasus Meteoroid Project, 329–36, 337, 345
Pegasus I, 331–33, 334
Pegasus II, 333–34
Pegasus III, 333–35
Performance Evaluation and Review Technique (PERT), 141, 286–88, 297
Phillips, Samuel C., 188, 254, 278, 289, 339, 373 ill.; and *Apollo 4*, 351–53; and *Apollo 8*, 364–65; and NASA budget, 188; and S-II program, 223, 230–32
Phillips report, 225–26
Piland, Robert O., 61
Pogo effect, 360–61, 362–63, 367, 368, 372
Point Barrow, (LSD), 305, 319 ill.
- Polaris (missile), 16
Polyurethane insulation, 175
Posiedon (barge), 305, 306 ill., 307
Powell, James T., 247
Powell, Luther E., 253
Pratt & Whitney Aircraft Co., 134, 135–38, 139 ill., 145, 152, 160, 189
Pregnant Guppy (cargo aircraft), 310–13, 315, 316 ill., 317–18
Prentice, R. W., 310
President's Scientific Advisory Committee (PSAC), 53, 67, 68, 113, 225
Priem, Richard J., 114
Program Control Center (MSFC), 283–85, 286 ill., 287–88, 289, 290–91, 292, 399
Program Control Office (GEM box), 273
Project Logistics Office (MSFC), 296, 303
Promise (barge), 305, 307
Propellant dispersion system (PDS), 255
Propellant utilization probe (PU probe), 181–82
Propellant utilization system (PU system), 177, 180–82, 338
Propellant, 7, 8, 11, 14, 25, 93; cryogenic, 89, 127, 129, 145, 149, 165, 174, 175, 177, 181, 182, 184, 188, 216, 345; gaseous, 89, 129; kerosene-based, 5, 89, 99, 102, 105, 127, 129, 232, 386–87; liquid, 7, 8, 36, 44–49, 51, 77, 107, 129, 130, 132, 133, 135, 137, 386, 400
Propulsion and Vehicle Engineering Laboratory (MSFC), 328
Public Affairs Office (NASA Hq.), 353
- Quality and Reliability Laboratory (MSFC), 367
Quality control, 183, 281–83, 366–67; F-1, 108, 109–10; H-1, 102–04; tank, 165, 207, 231–32; welding, 186, 217, 230
Quarles, Donald A., 40
- Raborn, William F., Jr., 284
RD-107 (Russian propulsion system), 386–87
RD-108, 386–87
Redstone (missile), 14, 15, 17, 19, 77, 83, 94, 141, 182, 195, 244, 350
Redstone (launch vehicle), 19, 20 ill., 21
Redstone Arsenal, 14–15, 30, 42, 69, 70, 311, 390
Redstone program, 15, 327
Rees, Eberhard F. M., 38 ill., 62, 158, 226, 230, 264–65, 277, 281, 282, 289, 296, 339, 350

STAGES TO SATURN

- Reliability and Quality Office (GEM box), 274
Reorganization: Douglas Aircraft, 278–80; NASA, 266–67, 269–71, 291; North American, 230–32
Research and Development Operations (R&DO, MSFC), 269, 270, 274, 286, 289, 290
Research Institute, University of Alabama, 395 ill.
Research Steering Committee on Manned Space Flight (Goett Committee), 41
Resident Managers Office (RMO), 277–78, 283
Rigi-mesh, 138, 145
RL-10 engine, 87, 127, 139 ill., 144, 326 ill., 334, 336; Centaur, used in, 134, 188; J-2, contributions to, 144, 147, 153; S-IV stage, used in, 137–38, 140, 188–89, 325; *See also* Cluster concept.
Rocketdyne Div., North American Aviation, Inc. (North American Rockwell Corp. from Sept. 1967), 15, 26, 76, 105 ill., 126 ill., 151 ill., 199–200, 280, 344, 361–62, 398; contracts, 29, 97, 104–05, 106, 141, 143, 148; production facilities, 98, 142–43; production innovations, 101, 118, 120–21; production problems, 101–04, 111–16; testing, 107, 111, 115, 123–24, 126, 142, 147, 152–53
Rockets, early, 7–14
Rosen, Milton W., 36, 39, 63, 65, 192, 193, 195
RP-1 (kerosene-based propellant), 5, 89, 164, 177, 192, 232; F-1, used in, 105, 107–08, 119–20, 127, 200; H-1, used in, 99, 102, 127; tanks, effect on, 192–93, 198
Rudolph, Arthur, 223, 273 ill., 293, 297, 351, 364, 399; and AS-501, 351–54, 357; and S-II program, 226, 231; management policies, 270–71, 275, 283–84, 288, 290–92
Ruud, Ralph H., 219, 231
- Sacramento Test Facility (SACTO, Douglas Aircraft Co.), 184–87, 280
Safety, 141, 185, 227, 229, 231
Salyut space station, 381, 387
Sanchini, Dominick, 110
Santa Susanna Field Laboratory, 142
SA-T (test booster stage), 79–80
Satellites, 17, 47, 161, 330; communications, 35, 38, 134, 394; weather, 25, 35, 135, 394
Saturn (launch vehicle), 21, 23, 56, 90 ill., 92, 99, 183, 396; in civilian programs, 39–41, 57; in military programs, 38–40, 57; nomenclature, 28, 36, 37, 60, 106, 161
Saturn A:
A-1, 47, 49
A-2, 47, 49
- Saturn B, 28 ill., 43
B-1, 47, 49
- Saturn C, 28 ill., 43
C-1, 48, 49, 51–53, 58, 59, 60 ill., 137, 160, 161, 209. *See also* Saturn I.
C-1B, 59–60, 143, 160, 161. *See also* Saturn IB.
C-2, 28 ill., 48, 49, 51–53, 57, 58, 209, 210
C-3, 28 ill., 48, 49, 58, 63, 210
C-4, 28 ill., 58, 157
C-5, 58–59, 60 ill., 65, 67, 160, 161, 162, 192. *See also* Saturn V.
- Saturn I, 3, 23, 28 ill., 30 ill., 61 ill., 70, 83–85, 139 ill., 161 ill., 183, 321–29, 331–36, 338, 381; design, 74–79, 189, 191, 324–27, 345; engines, 95, 97–98, 101, 137, 157, 256, 336; guidance system, 243–45, 249, 329, 349; liquid hydrogen fuel, 87, 89, 91, 325; 400; production, 196, 265, 299; 399; testing, 79–81, 323, 337. *See also* Air transport, Land transport, Pegasus project, Water transport.
- Saturn IB, 3, 20 ill., 23, 28 ill., 61 ill., 77, 84 ill., 85, 126–27, 155, 161 ill., 169 ill., 179 ill., 209, 278, 291, 306 ill., 316 ill., 321, 342 ill., 345, 377, 385 ill., 389 ill.; and ASTP program, 388–89; design, 38, 157, 162, 189, 191, 337–38; engines, 87, 94, 97, 98, 103, 143, 256, 338, 339; guidance system, 244, 245, 247, 249, 254, 329, 339, 344; liquid hydrogen fuel, 89, 91, 400; production, 71, 83, 185–86, 196, 266; and Skylab program, 382–83; testing, 38, 148, 338. *See also* Air transport, All-up concept, Land transport, Water transport.
- Saturn IB Program Office (MSFC), 270
- Saturn V, ii ill., 3–4, 7, 20 ill., 23, 28 ill., 61 ill., 70, 75 ill., 85, 126–27, 161 ill., 197 ill., 271, 297, 321, 354–55, 365 ill., 367–71, 378, 381; design, 157, 177, 189, 278, 288, 372, 400; engines, 87, 89, 101, 123, 125, 143, 148, 256, 339, 354, 357, 376–77; guidance system, 155, 241, 243–45, 247–49, 329, 357–59; liquid hydrogen fuel, 89, 91, 162, 400; production, 71, 185–86; and Skylab program, 379, 382; testing, 73, 188, 338, 345. *See also* Air transport, All-up concept, Manned lunar landing, Noise, Pogo effect, Quality control, Schedule delays, ST-124, Water transport, Welding.
- Saturn V Program Office (MSFC), 270–71, 273, 286 ill., 290–92. *See also* Government-contractor relations, Program Control Center, Quality control.

INDEX

- Saturn 500-F (interim facilities test vehicle), 351-52
Saturn-Apollo space vehicle (*See also* Apollo Saturn IB and V):
SA-1 (Saturn I), 98, 304-05, 323-24, 326, 327, 328
SA-2, 324, 325, 336
SA-3, 324, 325
SA-4, 324, 326 ill., 328
SA-5, 185, 244, 312, 323, 324, 326 ill., 327, 328
SA-6, 104, 327, 328, 329, 338
SA-7, 101, 104, 327, 329, 331
SA-8, 327, 331, 338, 334
SA-9, 244, 327, 331, 332
SA-10, 326, 327, 335
SA-201 (Saturn IB), 97
SA-202, 97
SA-203, 97
SA-204, 97
SA-205, 97
SA-206, 97
SA-209, 389
SA-211, 389
SA-514 (Saturn V), 389
SA-515, 389
Saturn Apollo Systems Integration Office (MSFC), 266
Saturn Booster Branch (Michoud Assembly Facility), 194
Saturn program, 39, 42, 47, 50-52, 59, 240, 272 ill., 262-63, 294, 400; contributions, 379, 397-99; cryogenics, advanced by, 134, 136-37, 143, 161-62, 398. *See also* F-1 engine, Government-contractor relations, H-1 engine, Management, Reorganization, Schedule delay.
Saturn stages:
S-I, 58, 77, 81, 82 ill., 89, 185, 189, 244, 325-27; Chrysler product, 83, 331, 333; MSFC product, 81, 334
S-IB, 77, 83, 89, 98, 102-03, 126, 148, 189
S-IC, 5, 6 ill., 75 ill., 89, 106, 111 ill., 127, 155, 189, 190, 197 ill., 205 ill., 208 ill., 212, 300 ill., 306 ill., 344, 352; flight performance, 212, 344, 357; proportions, 191-92, 196, 201, 206, 222, 354, 398; RP-1 fuel, 164, 192, 200, 232; testing, 69, 71-72, 73, 74, 196, 207, 209
S-II, 5, 6 ill., 58, 69, 127, 143, 155, 162, 189, 190, 191-92, 220-21 ill., 303 ill., 306 ill., 319 ill., 353, 398, 399; destruction of, 224, 229-30; flight performance, 212, 233, 357-58, 360-61, 367-68, 370-71; liquid hydrogen fuel, 43, 89, 209, 211; testing, 73, 74, 223-24
S-IV, 48, 49, 77, 81, 137, 139 ill., 161 ill., 169 ill., 182, 184, 189-90, 316 ill., 319 ill., 326 ill., 382; destruction of, 185, 186; flight performance, 183-84, 328; liquid hydrogen fuel, 89, 163-64, 325
S-IVB, 5, 83, 89, 143, 155, 157, 161 ill., 169 ill., 179 ill., 183, 186, 187 ill., 279 ill., 306 ill., 316 ill., 319 ill., 374; design, 162-64, 190, 212, 222; flight performance, 144, 147, 338-40; 343-44; 358-59; 361-62; 367-69; 371, 375; liquid hydrogen fuel, 164, 174; testing, 148-49, 184, 188
S-V, 48, 58, 137, 159, 265, 324, 325
Saturn Systems office (SSO, MSFC), 265-66, 270
Saturn Vehicle Team (Silverstein committee), 45, 47-51, 140
Schedule delay, 52-53, 68, 153, 160, 209, 223-32, 349, 352-54, 364-65, 376
Scheer, Julian W., 353
Schirra, Walter M., 343, 344
Schmidt, Dalton M., 238
Schneider, William C., 347, 357
Schomburg, August, 42
Schriever, Bernard A., 34, 228
Schweickart, Russell L., 368
Schwenk, Francis C., 47
Scott, David R., 368
Seal Beach Production Facilities, 69, 212, 215, 221 ill.
Seamans, Robert C., Jr., 55, 63, 67, 68, 113, 160, 312, 351
Shea, Joseph F., 65, 66, 226
Shepard, Alan B., 19, 20 ill.
Sidey, Hugh, 55
Siebel, Mathias P., 202, 262 ill.
Silverstein, Abe, 41, 44, 45, 46 ill., 62, 132, 133, 134, 136, 137
Silverstein committee. *See* Saturn Vehicle Team.
Skylab, 291, 317, 379, 381-85
Skylab 4, 385 ill.
Skylab program, 126, 127, 383-84
Slayton, Donald K., 389
Slidell Computer Facility, 68, 72, 390
Sloop, John L., 132, 133, 134
Smith, Robert G., 287
Smith, Ted, 167, 189
Smith, Whitney G., 201
Smithsonian Institution, 332
Smolensky, Stanley M., 296
Sneed, Bill H., 267, 291
Solar cells, 332, 384

STAGES TO SATURN

- Solar Div. International Harvester Co., 102, 254
Sorensen, Theodore C., 54
Sounding rockets, 14, 17
Soviet Union, 18, 53, 54, 55, 381, 386, 387, 388, 400
Soyuz spacecraft, 381, 387, 389 ill.
Soyuz 10, 381
Soyuz 11, 381
Space and Information Systems Div. (S&ID), North American, 222, 223, 224–27, 231
Space race, 17, 19, 21, 33, 53, 54, 55, 104, 381, 401
Space Shuttle, 291, 400
Space Task Group (STG, forerunner of MSC), 61, 62, 63
Sparkman, John J., 390
Speer, Fridtjof A., 323
Spent stage laboratory. *See* Orbital Workshop.
Spider beam, 78, 82 ill.
Sputnik I, 18, 26, 381, 386
Sputnik II, 18
ST-80 stabilized platform, 243
ST-90 guidance platform, 243, 244, 245
ST-142 stabilized platform, 243, 244 ill., 245, 248, 249, 251, 253
Stafford, Thomas P., 368, 369, 389
Stever, H. Guyford, 33, 34
Stewart, Donald L., 317
Stewart, Homer J., 51
Stoner, George H., 194, 195
Storms, Harrison A., 225, 227, 229, 230, 231
Stress corrosion, 101
Studhalter, W. R., 150
Stuhlinger, Ernst, 38 ill., 74, 335
Super Guppy (cargo aircraft), 314–15, 316 ill., 317–18
Super-Jupiter (launch vehicle), 25–27
Surveyor mission, 137
Sutton, George P., 45
Sweat, Sidney J., 253
Swigert, John L., Jr., 375
Symington, Stuart, 390
Systems Engineering Office (GEM box), 274
- Tank, 29, 30 ill., 81, 82 ill., 122, 155, 169 ill., 180, 187 ill., 195, 354 design, 76–78, 146–47, 164–65, 177, 199, 211–12, 213, 387–88; problem phases, 185, 218–19, 223, 231, 282, 324; production techniques, 166–68, 170–71, 206, 213–14, 216; pressurization of, 144, 177–78, 180, 198, 211–17.
- See also* Cluster concept, Insulation, Propellant utilization system.
Taurus (LSD), 305
Technology transfer, 379, 394–396
Technology utilization program, 397
Teflon, 102, 353
Television, 327, 347, 356, 357, 368, 369–70
Test Office (GEM box), 273
Testing, 187 ill., 236, 238, 282, 353, 358; flight, 184, 323; ground, 183, 184, 196, 347; hydrostatic, 171, 206, 223; load, 195, 206; static test firing, 148, 149, 184, 187, 188, 206, 216, 230, 367; test stands, 186, 206, 207; x-ray tests, 170–71, 206
Thompson, Jerry, 113, 145
Thor (IRBM Missile), 14, 17, 19, 309; in civilian programs, 21, 34; adapted to Saturn program, 91, 95, 127, 141, 164–65, 177, 189–90
Thor (launch vehicle), 19, 21, 25
Thor-Able (launch vehicle), 36, 101
Thor-Agena, 61 ill.
Thor-Delta, 61 ill., 240
Thor-Jupiter engine (S-3D), 29, 95, 97, 100
Thrust chamber, 16, 119, 122 ill., 145
Tiny Tim (air-to-ground rocket), 11
Titan (ICBM missile), 17, 21, 34, 35, 37, 43, 44
Titan (launch vehicle), 17, 43, 44, 161, 361, 388
Titan C, 39
Titan I, 36, 91
Titan II, 20 ill., 61 ill., 243, 349
Titov, Gherman S., 20
Transport. *See* Air transport, Land transport, Water transport.
Trott, Jack, 201
Tsiolkovsky, Konstantin E., 8, 129–30
Tugboat, 303, 304, 307, 308
Turbopump, 93, 94 ill., 116–17, 118, 119, 146
Tyson, Overton S., 188
- Unexcelled Chemical Corp., 317
United Aircraft Corp., 134
Urlaub, Matthew W., 194, 207, 209, 263
U.S.S. *Hornet* (*Apollo 11* recovery ship), 372
- V-2 (rocket), 9, 12, 14, 15, 16 ill., 91, 195, 242, 244, 350, 386, 400
Vanguard (launch vehicle), 16 ill., 18, 19, 34, 36, 91, 141, 236
Vanguard I (satellite), 16 ill., 19

INDEX

- Vanguard, Project, 17–18, 19, 26
Venus (planet), 54
Viking (launch vehicle stage), 17
Viking (sounding rocket), 17
Vladimirov, Leonid, 387, 388
Vogt, Paul, 231
von Braun, Werner, 10 ill., 20 ill., 38 ill., 68 ill., 69, 262 ill., 277 ill., 287, 373 ill.; ABMA research, 26, 28, 33–34, 37; all-up concept doubts, 348, 350–51; early career, 11, 14–15; Huntsville, influence on, 391–95; liquid hydrogen fuel doubts, 44–46, 400; management policies, 62, 261–67, 287, 289–90, 293–94; MSFC director, 42, 57, 124, 245–46, 355, 357, 359–61, 391; Pegasus program evaluation, 334, 336, 337; Pregnant Guppy, support for, 310–11; schedule delay handling, 157–58, 223–24, 227–29, 231, 364, 366
von Braun team, 14, 38 ill., 56, 259, 261, 391; ABMA research, 18, 23, 27–28, 31, 33; conservatism, 15, 333–34, 349; contractor relations, 82, 266; inertial guidance development, 242, 244; NASA, transfer to, 21, 40–42, 44, 69
von Kármán, Theodore H., 130
Voshkod I, 21
Voshkod II, 22
Vostok launch vehicle, 387
Vostok (satellite), 387
Vostok I, 19
Vostok II, 20
Wac Corporal (sounding rocket), 11, 14
Water transport, 253–54, 293, 298, 301, 302, 318
Webb, James E., 54, 55, 67, 68 ill., 210, 288, 290–91, 348, 353, 366, 399
Weidner, Hermann K., 141, 268
Welding, 186, 221 ill., 396–97; defects, 103, 207, 224, 230, 254, 282, 352; innovations, 202–03, 218–19, 222; quality control, 191, 194, 212, 217, 282; techniques, 118, 166–67, 170, 191, 195
“Wet workshop.” *See* Orbital Workshop.
White, Edward H., II, 231
White Sands Proving Ground, N. Mex., 14, 16 ill.
Wiesman, Walter F., 393
Wiesner, Jerome B., 53, 67, 68 ill.
Williams, Frank L., 264, 350
Wilson, Earl, 188–89
Wilson, Norm, 218

XLR-15 engine. *See* RL-10 engine.
Xerox, 287

Yarchin, Sam, 224, 226, 230, 231
York, Herbert F., 38, 39
Young, John W., 368
Young, Robert, 269, 289, 350

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